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# Journal of the ROYAL NAVAL SCIENTIFIC SERVICE

Vol. 23, No. 2

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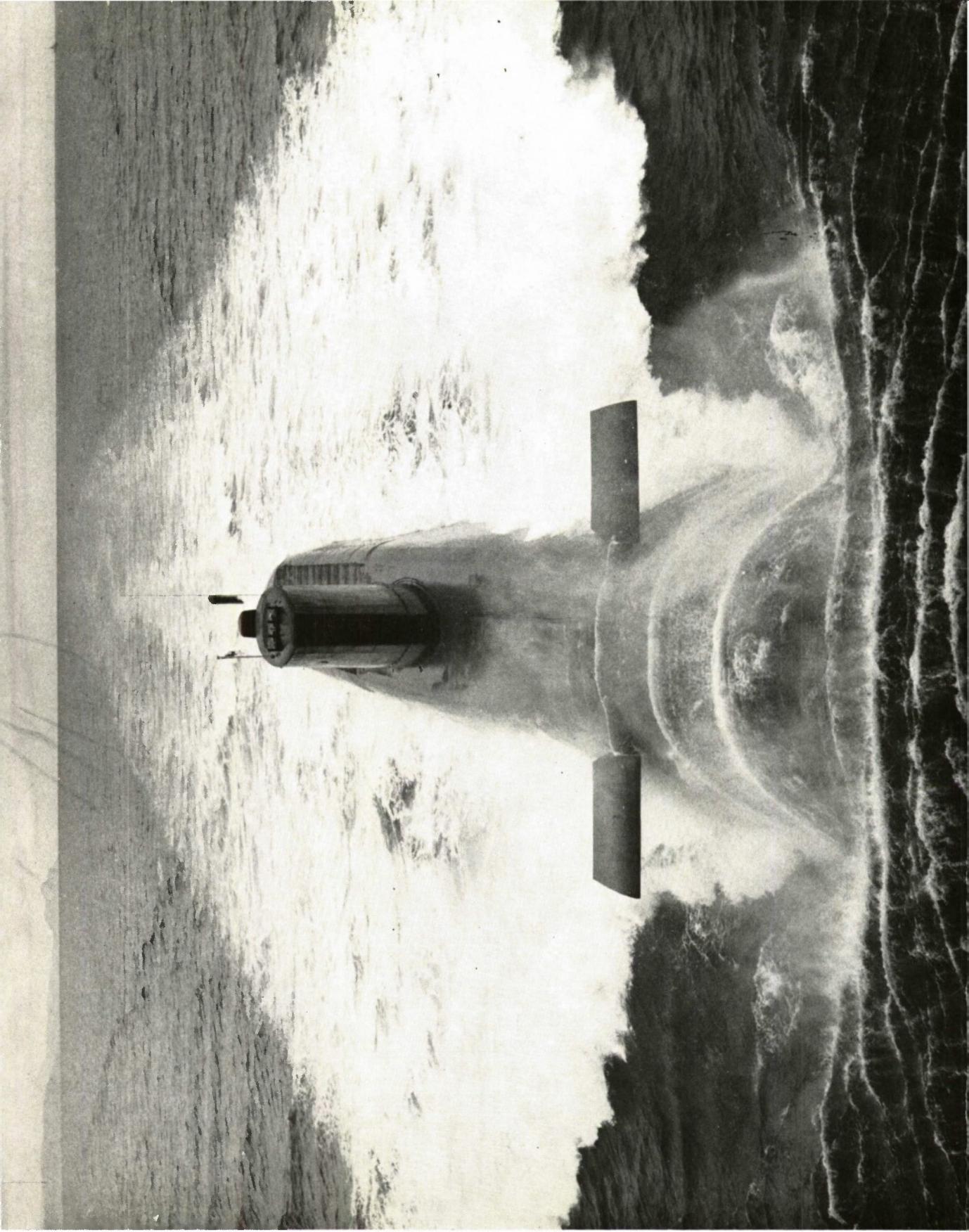
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H.M.S/M. Resolution on Trials

# IMPROVEMENTS IN MICROWAVE SLOT ARRAY RADIATORS

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## Introduction

In order to carry out a programme of work on inertialess scanned aerial arrays<sup>(1)</sup> it has been necessary to produce a suitable radiating aperture, formed by the stacking of a number of linear arrays of radiators. To produce a pencil beam of width of the order 1° to half power, with no higher order diffracted beams, we require of the order 10,000 radiators, in 100 rows of 100. Previous work has shown that for the case considered this is best achieved by the use of slot radiators in waveguide, the advantages of other forms of radiator being outweighed by greater complexity, cost and weight. Improvements have been made in the bandwidth and radiation patterns of slotted linear arrays for this application.

## The Waveguide

In order to prevent the formation of higher order diffracted beams under all scanning conditions it is necessary that the waveguide arrays may be stacked at a pitch of about a half wavelength. In the case considered displaced slots in the H-plane wall of the waveguide have been used as these are found more successful than inclined slots in the E-plane wall and do not have the disadvantage of radiating cross polarized lobes. It is therefore necessary to take special measures to pack the arrays sufficiently closely. The method adopted is to use

ridged waveguide which can have a much smaller H-plane dimension than conventional rectangular waveguide in any given frequency band. The work discussed here was carried out in C-band (5 to 6 GHz), and a ridged waveguide section was used giving a stacking pitch of about one inch, as compared with the two inch H-plane dimension of the standard rectangular waveguide.

Early experiments on waveguide of this section<sup>(2)</sup> were carried out by manufacturing waveguide from a milled ridged channel with a top plate screwed or swaged on to complete the section. This technique made possible investigations with waveguides of different cut-off frequencies for the optimizing of dimensions, particularly having regard to slot bandwidth and the stacking pitch of the arrays.

On extending this work to stacks of arrays and further investigations on broader frequency band working it has been found that satisfactory results are more cheaply and reliably obtained by using drawn waveguide to the dimensions chosen. A suitable ridged drawn aluminium waveguide of section shown in Fig. 1 has been specially produced for this work and is now available in quantity. The cut-off frequency is 4.693 GHz, a frequency not far below the working band of the array. This is an intentional choice yielding a resonant slot radiator bandwidth of a little over 10%<sup>(2)</sup>.

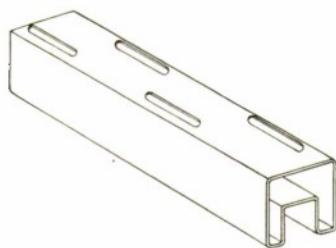
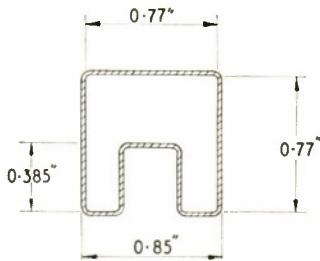


FIG. 1. The Slotted Ridged Waveguide.



### Array of Slots

In the design of the arrays discussed here the amplitude distribution along the array of slots taken as the design aim is  $\frac{1}{7} + \frac{6}{7} \cos^2\theta$ .

This is a commonly used function giving a reasonable compromise between gain and side lobe level, the latter having a theoretical level of 36 decibels below the level of the main beam radiation.

It is common experience that it is never possible to achieve the theoretical level of side lobes in a particular case, the difference between theory and performance being greater as a lower level of side lobes is attempted. In addition the performance obtained with an array of resonant slots at the design frequency quickly deteriorates with change of frequency, due to the change in the coupling factor of the slot radiators. Each slot being usually resonant at the design frequency causes the power radiated to fall at frequencies higher or lower. Also, at frequencies other than slot resonance, the slot is reactive and introduces either advance or retard in the phase of the remaining energy flowing past it along the waveguide to the next slot. The magnitude of the phase shift is a function of the slot coupling factor. This phase shift causes deterioration of the radiation pattern.

In the present design therefore, on the basis of past experience on linear arrays, the following points have been considered. First, an attempt has been made to achieve a radiation pattern nearer to the theoretical at the design frequency. Second, this performance has been maintained by aiming at holding the amplitude distribution along the array near to the desired function over the maximum possible frequency band. Third, phase shift past the slot radiators has been investigated and its effect minimized.

Having these points in mind the following design procedure was adopted.

### Slot Coupling Factor and Displacement

The coupling factor of the type of slot used is determined by the displacement of its centre line from that of the waveguide. Zero coupling is obtained with a slot cut on the centre line. The phase of the radiation from a slot is changed by  $180^\circ$  if it is transferred to the opposite side of the waveguide centre line. To produce in-phase radiators on a half wavelength spaced linear array of slots alternate slots are cut on opposite sides of the centre line (Fig. 1). The required range of coupling factors needed for the chosen amplitude distribution can be seen in Fig. 2 where the case of a 62 slot array having 0.1% power in the end load is illustrated. It is important to note that, although coupling factors are required up to over 0.4, about one third of the radiators must have coupling factors below 0.025. In establishing the law relating coupling factor and slot displacement it is therefore important to achieve high accuracy in the small quantities measured, particularly as errors in the first couplers of a series fed array are cumulative in effect.

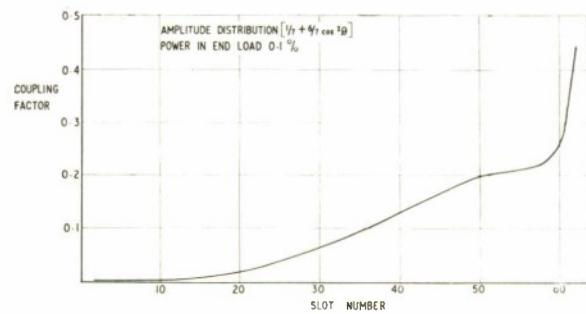


FIG. 2. Coupling Factor as a Function of Slot Number in the Array.

The law was established by measurement on test lengths of groups of slots of constant displacement. In the case of standard rectangular waveguide it is only necessary to establish the coefficient of a sine<sup>2</sup> law, but this is not applicable to the ridged waveguide. Fig. 3 shows the curve obtained from eight test lengths of slotted waveguide.

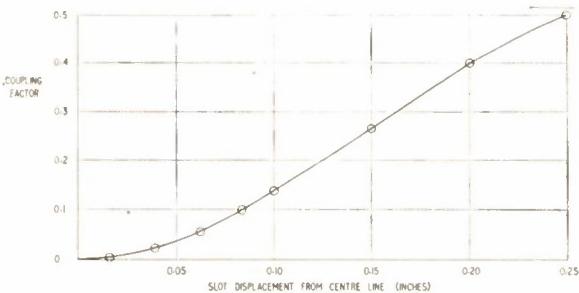


FIG. 3. Coupling Factor as a Function of Slot Displacement from the Waveguide Centre Line.

### Slot Length and Resonant Frequency

The resonant frequency of the individual slot is a function of its periphery, and in the case of the particular arrays under discussion it is also affected by the presence of a dielectric tape which is placed over the slots as weatherproofing, since the arrays are intended as part of an aerial system needing no protective radome.

It has been normal practice to design the slot radiators to be resonant at the design frequency of the array, normally at the centre of the working frequency band, resonance being defined in this case as the frequency at which a given slot couples a maximum of power out of the waveguide. This method gives the same distortion of aperture amplitude distribution at each end of the frequency band. However measurements have shown that the phase shift past the slot along the feed waveguide is not zero at resonance as defined by maximum radiated

power, but at a frequency above resonance in the case considered. Fig. 4 illustrates this for the case of a slot of coupling factor 0.2. This means that distortion of the radiated phase front due to this cause is greater at one end of the frequency band than at the other. Both computation and measurement have shown that better radiation patterns are

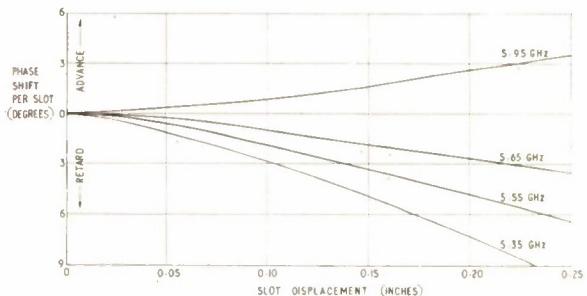


FIG. 5. Phase Shift Past a Slot Resonant at 5.65 GHz as a Function of Displacement, at Various Frequencies.

obtained over a given frequency band if the slot dimensions are so chosen that the frequency of zero phase shift past the slot, rather than the frequency of maximum radiated power, is at the centre of the working band. This condition gives balanced deterioration of radiation patterns at either end of the band.

Fig. 5 shows measured phase shift past a slot resonant (maximum coupling) at 5.6 GHz as a function of displacement, at various frequencies.

### Improvement of Array Performance

Since the nature of the resonant slot radiators is such that the power radiated falls at frequencies on either side of resonance, the power distribution along the array is distorted at each end of the frequency band as illustrated in Fig. 6. This illus-

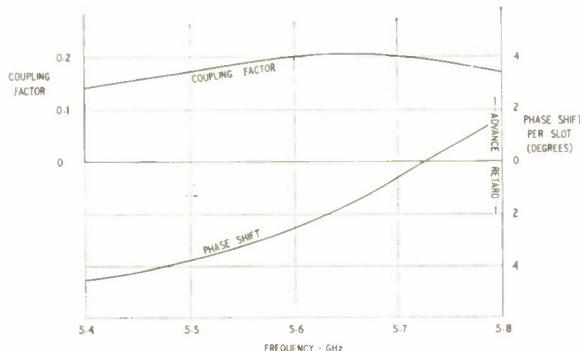


FIG. 4. Coupling Factor and Phase Shift of a Resonant Slot as a Function of Frequency.

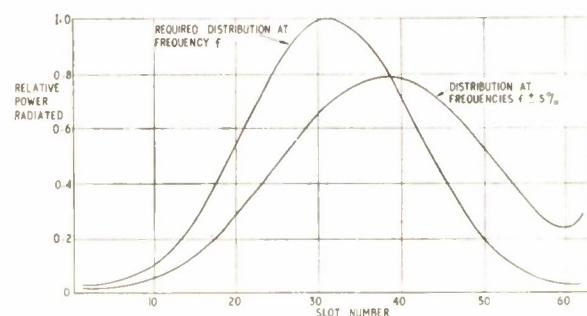


FIG. 6. Array Power Distribution Showing Deterioration at the Ends of a 10% Frequency Band.

trates the effect on a  $\frac{1}{7} + \frac{6}{7} \cos^2$  distribution

when the slots are radiating half power, which occurs at  $\pm 5\%$  frequency deviation in the case considered. The distribution is broadened in an asymmetric manner, the taper at the load end decreasing and the power absorbed in the end load increasing from the design value of 0.1% to approximately 4%. This, together with the cumulative phase shift past the slots, accounts for the deterioration in radiation patterns at the ends of the band.

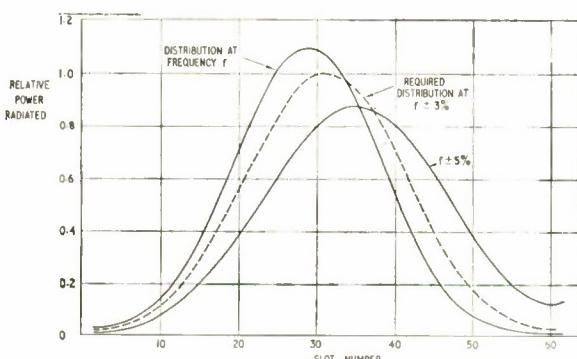


FIG. 7. Compensated Array Power Distribution.

It would seem that an improvement in this performance may be achieved by designing at centre-band to give a distribution which is distorted in the opposite sense to that illustrated in Fig. 6 for conventional design. Such a distorted centre-band distribution is illustrated in Fig. 7, the upper curve. It will be seen that this results in a much smaller distortion in the distribution at the ends of the frequency band of  $\pm 5\%$ . In addition the distribution is correct now at two points in the band (approximately  $\pm 3\%$ ), instead of centre-band only, and much less power is lost in the end load. The new centre-band distribution is produced by computing slot coupling factors for the required distribution and, before converting these into slot dis-

placements, multiplying by a factor  $\frac{4}{3}$ . Thus,

using slot radiators which couple half power at band ends, we have coupling factors varying

between  $\frac{4}{3}$  and  $\frac{2}{3}$  of the correct value, the

correct value being obtained at two points in the band. This compares with the conventional method of design where coupling factors vary between correct and half of correct value, and are correct only at one point in the band.

Before illustrating the improvement in radiation patterns produced by this type of distribution some consideration is needed of the price paid in terms of aerial gain. On looking at the new centre-band distribution illustrated in Fig. 7 it is clear that the

$\frac{4}{3}$  multiplier reduces the aperture efficiency, the power radiated being concentrated more towards the aperture centre, with a consequent beam broadening and loss of gain. To illustrate the magnitude of this effect Fig. 8 shows a computed curve relating the coupling factor multiplier and the rela-

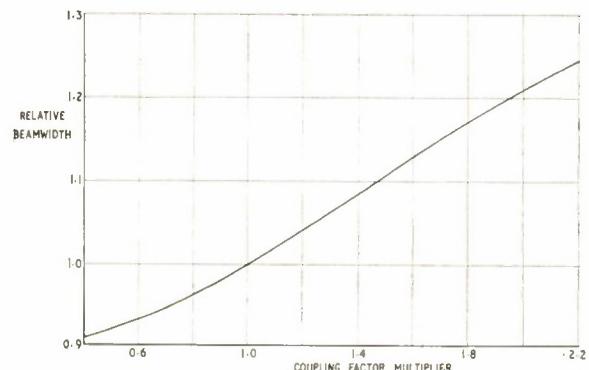


FIG. 8. Variation of Beamwidth with Element Coupling Factor Multiplier (Computed).

tive beamwidth, for the particular distribution considered. Thus if the case is taken of a multiplier of 1.33 as already mentioned we see that the beamwidth increases in ratio 1.07, representing a loss of gain at centre band of about 0.3 dB. This loss reduces towards the ends of the band as the distribution becomes less tapered.

Fig. 9 illustrates the improvement in the radiation pattern over a frequency band obtained by the use of a multiplier. The plot shows the highest side lobe in the radiation pattern as a function of

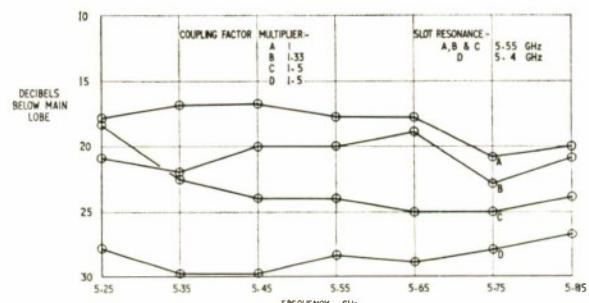


FIG. 9. Highest Side Lobe in the Radiation Pattern over a Frequency Band, for Different Multipliers.

frequency for four different arrays. Array 'A' is designed by the conventional method for  $\frac{1}{7} + \frac{6}{7}$  cosine<sup>2</sup> distribution at 5550 Mc/s and arrays 'B' and 'C' illustrate the effect of multiplying slot coupling factors by 1.33 and 1.5 respectively. Array 'D' differs from 'C' in having slot radiators resonant at a lower frequency, illustrating the effect of phase and amplitude distribution combining to give a good result.

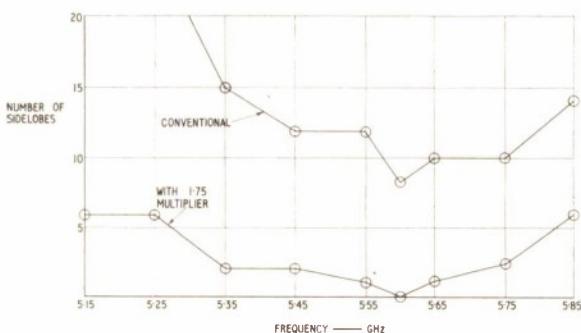


FIG. 10. Number of Side Lobes in the Radiation Pattern at a Level Greater than 30 dB below the Main Lobe.

The improvement in radiation patterns is also illustrated in Fig. 10 where a plot is shown of the number of side lobes at a level greater than 30 dB below the main beam as a function of frequency. The cases compared are a conventional array and one having a 1.75 coupling factor multiplier.

Some radiation patterns at the centre of the frequency band are illustrated in Fig. 11. This illustrates very clearly that the fact of over-coupling the slots at band centre has considerably reduced the all-round side lobe level. This improvement is to an extent greater than expected from the slight increase in amplitude taper produced by the multiplier. The reason for this is not clear.

Fig. 11 also illustrates the formation of grating lobes in the conventional design of array, and their gradual suppression with increasing coupling factor multiplier. This behaviour would be consistent with a phase perturbation on transmission through the slot, the sign of which was dependent on direction of displacement of the slot from the centre line of the waveguide. Measurements have shown that such a phase shift does exist for slots of small displacement, in fact those having their width partly covering the centre line. It seems likely that current work will yield a complete explanation of the grating lobe levels illustrated in the radiation patterns of Fig. 11.

## Conclusions

An investigation into possible methods of improving the bandwidth of series fed arrays of radiating slots has yielded a technique which gives a marked improvement in performance at the expense of a small amount of aerial gain at the centre of the working frequency band. It is possible to produce very good radiation patterns over a 10% frequency band with a small loss of aerial gain, and quite tolerable results can be obtained over a 30% band if a reduction of aerial gain of between 2 and 3 dB is acceptable.

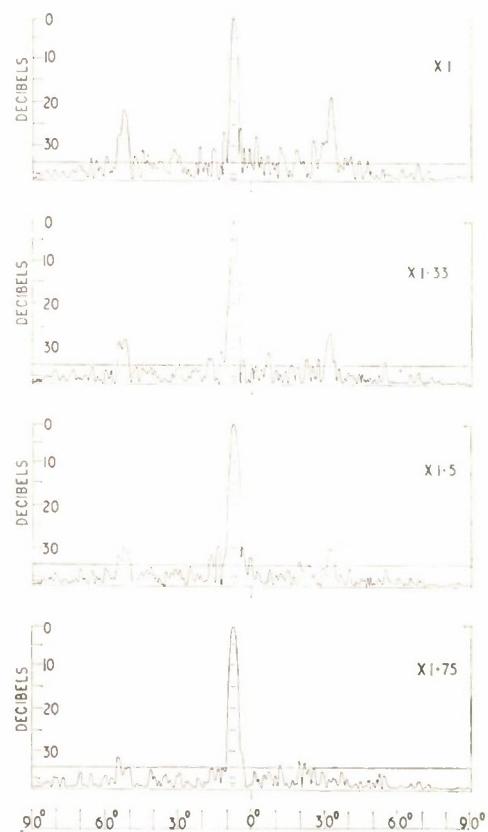


FIG. 11. Radiation Pattern Improvement with Increasing Coupling Factor Multiplier.

## Acknowledgements

The measurements involved in this work were carried out by Mr. J. C. Sherren and Mr. D. W. Marshall and thanks are due to Mr. B. R. Gladman for the computation of the values plotted in Fig. 8.

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- (2) *A.S.W.E. Laboratory Note XRA-64-3*. D. N. Keep and N. E. Porter. "The Bandwidth Properties of Arrays of Shunt Slots in Single Ridged C-band Waveguide."

## EXPERIMENTAL STUDIES OF MOTION SICKNESS DRUGS

**J. J. Brand, M.B., B.Sc.**

*Royal Naval Medical School*

This paper is based on the findings made to date in a programme of research into the causation and prevention of motion sickness. This is being undertaken at the Royal Naval Medical School, Alverstoke, by kind permission of the Medical Director-General of the Navy, and the Medical Officer-in-Charge, Surgeon Captain S. Miles. It is being conducted under the direction of Professor W. L. M. Perry of the Department of Pharmacology of Edinburgh University and Professor R. A. McCance of Cambridge and with the backing of the Survival at Sea Sub-committee of the Royal Naval Personnel Research Committee of the Medical Research Council.

The work so far has consisted mainly of a detailed study and analysis of the previous experimental work in this field, with special reference to the use of drugs in the prevention and treatment of the condition. This has been undertaken as a basis for further systematic investigation of the subject. This paper is an outline of our findings so far; these are now reported more fully in "Pharmacological Reviews" (Brand and Perry, 1966). It has been our aim in studying the experiments on drugs used in motion sickness to clarify the present status of our knowledge derived from experiments in both man and animals. We have tried to determine which of the preparations used in man can be clearly shown to be effective, and by so doing perhaps gain some insight into their mechanism of action, and also to see what laboratory tests are available for the evaluation of such drugs, and what correlation exists between the results obtained in this way and in field trials.

In the vast literature on the subject there is very little cohesion, and the results of the various isolated experiments made under field or

laboratory conditions often appear contradictory. In spite of the enormous amount that has been written there are still too few well established facts. The first point then, is to consider in what ways the action of drugs on sickness may be studied in man, and to take a look at some of the methods of study which have been used by investigators over the past 20 years. It was of course only about 20 years ago that any serious research on the subject was undertaken in the realization that it would become necessary to transport large numbers of troops by sea and air for various missions in the Second World War.

The actual method which gives rise to the nauseating motion appears to be relatively unimportant in this sort of study: it suffices that it shall be such as to produce vomiting in a fairly high proportion of unprotected subjects so that the protective effect of the drug may be clearly shown. Earlier workers would certainly not have agreed with this statement; to them airsickness and car sickness for example, were separate entities, and when the effectiveness of the drugs under study appeared to vary with the form of motion to which the subjects were exposed their beliefs seemed to be confirmed. The duration of the nauseating motion appears to be much more important in drug trials than is its quality, and it is failure to allow for this variable, among others, which probably led to the discrepancies which occurred in the different trials. Some of the methods of study which have been used are shown in Table 1. This list is clearly not exhaustive and any technique by which a subject is exposed to the effects of unfamiliar and conflicting labyrinthine stimuli can probably be relied upon to produce symptoms of motion sickness. This has been well shown in

**TABLE I. Methods of Study.****A. MAN**

## (1) Field Trials

- (a) Naturally occurring motion:  
Ships, aircraft  
(b) Artificially induced motion:  
Life-rafts, swings, lifts
- } End point = vomiting

## (2) Laboratory tests

- (a) Chemical emetics: apomorphine } End point = vomiting  
(b) Tests of Labyrinthine function:  
Rotating platforms                   } Nystagmus or "After sensa-  
Parallel swings                      tions" times

**B. ANIMALS**

- (1) General pharmacological tests: *in vitro* techniques  
*e.g.* v. Acetylcholine  
v. Histamine
- (2) Production of swing sickness in dogs
- (3) Antagonism of effects of Intracarotid D.F.P.  
("Adverse Syndrome")
- (4) Chemical emetic agents; apomorphine, digitalis
- (5) Tests of labyrinthine function:  
Rotating platforms, parallel swings  
Labyrinthine righting reflexes

recent American studies at Pensacola where head movements in a sagittal or coronal plane have been superimposed upon rotational stimuli, giving rise to Canal Sickness. (Kennedy, R. S. and Graybiel, A. 1962). Such methods have only recently been used in the evaluation of drugs (Wood, C. D., Graybiel, A., McDonough, R. G., Kennedy, R. S., 1965).

As regards the action of drugs in man there are then two main groups of methods of study which are available: one may either expose the subjects to motion of various kinds (which may be either naturally occurring or artificially induced) and estimate the protection afforded by the drugs in question. Alternatively one may study the effect of drugs on subjects in the laboratory, employing tests which for various reasons might be considered relevant. These are for example, the prevention of vomiting after administration of chemical emetic substances such as apomorphine, or the study of the various measurable effects which result when men are exposed to the effects of rotation or the parallel swing. The parameters used include nystagmus or sensations of after-turning with rotational stimuli and compensatory eye movements after parallel swinging.

In animals the main methods of study have been as shown in Table 1(B). It is at once apparent that a great variety of tests has been used in an attempt to establish a correlation between effects observed in animals under laboratory conditions, and in field trials in man.

This paper deals mainly with studies in man: if these are considered in a little more detail, one can attempt to show how some of the discrepancies in the various experimental findings may have come about.

The first controlled studies employing such essentials as the random allocation of drugs on a double blind basis were made some 20 years ago when Holling, McArdle and Trotter (1944) exposed soldiers to natural wave motion in coastal trawlers. They were evaluating the drugs which were available at that time, *viz.*, 1-hyoscine, atropine, 1-hyoscyamine, and various barbiturates. Antihistamine drugs were then in their infancy, and it was not until five years later that Gay and Carliner were first able to confirm an accidental observation which had suggested that an antihistamine drug might be effective in the prophylaxis of motion sickness. This was diphenhydramine, as Dramamine. This particular experiment was carried out in a troopship, but many other techniques have been employed to assess the effects of motion sickness drugs in man, and these are set out in Table 2. They may be seen to fall naturally into two groups: (a) those involving motion of short duration, *i.e.* less than eight hours, and (b) those where motion of longer duration was used, usually about 48 hours. (Group (a) includes coastal trawlers, assault craft, and fast patrol boats, aircraft, life rafts, swings and a linear accelerator or lift. Group (b) includes the large American series of studies in troopships on the New York-Bremerhaven crossings in the early 1950s, and also a study made in Swedish minesweepers. All of these were, needless to say, effective in producing symptoms of motion sickness in all but the most resistant subjects.

However, when the results of such studies are examined more closely it is found that they are frequently conflicting and it seems that many of the discrepancies may be due to the experimental design. In general, after 1950 American workers used troopships for their experiments while in Britain we used the method devised by Glaser and Hervey in 1952, namely the exposure of men to the motion of artificial waves in a large tank. After the success of diphenhydramine (*i.e.* Dramamine and Benadryl) other chemically similar drugs were also shown to be effective in troopships. These were promethazine (Phenergan, Avomine) meclozine (Ancolan, Bonamine, Postafene), and cyclizine (Marzine, Marezine). In Britain however, using life-rafts and artificial waves, hyoscine was shown to be greatly superior to any other drug, and though promethazine and diphenhydramine were found to have some effect they were clearly much less active (Glaser and Hervey 1952). Again, though some effect was shown for cyclizine, meclo-

TABLE 2. Methods of Study in Man.

## A. MOTION OF SHORT DURATION (under 8 hours)

Method	Range of Duration	Author
(a) Small Ships		
(i) Coastal Trawlers	4 - 6	Holling <i>et al.</i> 1944
(ii) Assault craft	4	Hill and Guest, 1945
(iii) F.P.B's headed into waves	1½ - 4	Glaser and Hervey, 1951
(b) Aircraft		
(i) Routine training and trooping flights	4 - 7	Lilienthal, 1945
(ii) Simulated turbulence using standard manœuvres	1	Strickland and Hahn, 1949
(c) Life Rafts and Artificial Waves	1	Glaser and Hervey, 1952
(d) Swings (14 ft. radius 150° arc)	20 mins	Smith and Hemingway, 1946
(e) Vertical accelerator (Lift)	20 mins	Johnson, Wendt, 1964
B. MOTION OF LONG DURATION (48 hours)		
(a) Troopships on N. Atlantic crossings	48	Gay and Carliner, 1949
(b) Naval Minesweepers on routine cruise	48	Arner <i>et al.</i> 1958

zine was found to be no better than a placebo (Glaser and McCance 1959). American workers on the other hand found that 1-hyoscine was ineffective in preventing vomiting in troopships and gave rise to a high incidence of side-effects. (Chinn 1956).

It now appears that these findings are, in fact, reconcilable, if due consideration is given to the variables involved in the field studies, and these are outlined in Table 3. This table sets out the main variables which must be taken into consideration in designing any field trial of motion sickness drugs: it would seem that failure to afford them adequate consideration has led to a great deal of confusion in the past.

It has already been shown how the duration of the causal motion has varied in different experiments, and this must also be true of the severity of the motion in any experimental situations where this variable is uncontrolled. These factors

TABLE 3. Variables in Field Trials.

- (1) Duration of causal motion (20 mins. to 48 hours)
- (2) Severity of causal motion (Life-raft; Troopships—variable weather conditions)
- (3) Individual susceptibility\*
- (4) Speed of absorption and duration of action of drug under study (See (1) and (2) above)
- (5) Size of dose given: dose/response relationships
- (6) Parameter used to determine effectiveness

\* Sensitivity of labyrinth to angular accelerations follows normal distribution pattern (Hulk and Jongkees, 1948); the distribution of sensitivity to linear accelerations has not been determined.

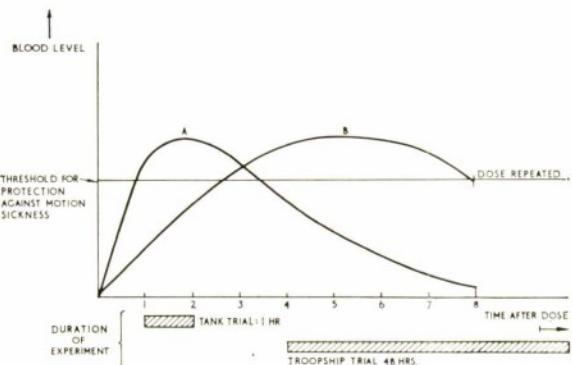


FIG. 1. Relationship of Effect to Speed of Absorption and duration of action.

considered together with the speed of absorption and duration of action of the drug under study may readily explain some of the conflicting results obtained. This consideration is shown diagrammatically in Fig. 1 which depicts the relationship between effective blood level of a motion sickness drug and its rate of absorption or excretion. It is evident that a speedily absorbed short-acting drug may prove highly efficient against severe motion experienced one hour after dosage and lasting for only one hour, whereas the slowly absorbed drug of longer duration of action, might be ineffective under these conditions yet prove very effective over a period of 48 hours especially if repeated at eight-hourly intervals. Where the motion is of long duration the protective effect of the short-acting drug may well be obscured. There is now some evidence that the absorption

and excretion curves of l-hyoscine and promethazine resemble those represented here as drugs A and B, (Brand, J. J. and Colquhoun, W. P. 1964), but it should be emphasized that such information for even these well-known drugs is incomplete, and many studies were undertaken in the absence of such data (Bain, W. A., Broadbent, J. L. and Warin, R. P., 1949).

Considering the second variable listed in Table 3, *viz.* the severity of the causal motion, this must clearly be different in each trial. There must also be a difference in the individual susceptibility of the subjects who took part. These two factors taken in conjunction will give rise to a different incidence of vomiting among the subjects in the placebo group in any given trial, and necessarily to a different degree of protection apparently afforded by the same drug in different trials. The range of incidence of vomiting in the placebo groups found in the various field trials, where different kinds of motion were used, is from 6 - 75%. This variable, resulting mainly from the interaction of the first three factors given in the table makes any comparison of data from trials in different situations very difficult indeed but underlines the importance of including a placebo group in any trial of this nature to provide a standard against which the efficacy of any drug may then be judged.

It is now possible, by careful assessment of all the data derived from the various experiments, to state that there are five drugs whose potency against motion sickness is undoubtedly and which have proved their worth in a variety of different situations. They are l-hyoscine (Scopolamine), meclozine (Bonamine, Postafene, Ancolan), cyclizine (Marazine or Marezine), promethazine (Avomine or Phenergan), and diphenhydramine (Dramamine and Benadryl). There are also other drugs chemically similar to the above whose efficacy is less clearly defined. It has not been possible, until recently to say much more about them beyond the simple fact that they are all effective to a greater or lesser degree. It has certainly not been possible to define the drug of choice on any grounds save those of rather indefinite information about duration of action or supposed absence of side effects.

This leads to the fifth factor mentioned in Table 3, *viz.*, the size of dose used. In most of the studies the drugs have been given at single fixed dose levels *e.g.* 1 mg. of hyoscine hydrobromide or 25 mg. of promethazine hydrochloride. Very few studies have been made where the drugs have been given at different dose levels in the same experiment, *i.e.*, there has been no attempt to define the dose/response relationships of the effective drugs. This means that practically nothing was known about their range of activity at therapeutic dose levels.

This gap in our knowledge assumes the greatest significance when it is appreciated that in the absence of such data it is impossible to assess the relative potencies of these drugs in establishing a correlation with any laboratory test. The absence of such information is also most unfortunate because all the effective drugs have undesirable side-effects in the doses at which they are commonly used. For example l-hyoscine may impair mental performance and cause dry mouth and blurred vision, and, in common with the antihistamine drugs it has a central depressant action. However it now seems possible that one may be able to reduce the dosage of the effective drugs to levels at which their side-effects cease to be troublesome although their protective effects are maintained. In other words the dose/response curves for these effects might well have different slopes. Further study is necessary to clarify this.

It is not yet clear whether some impairment of mental performance is inevitable if protection against motion sickness is to be secured and studies are proposed to obtain dose/response information for the effects of drugs on mental performance and compare this with similar information for protection against vomiting induced by motion. Recent experiments have indicated that, in the case of hyoscine the effects of the drug on mental performance can be minimized by reducing the dose (Colquhoun and Brand 1964). As stated above there is very little information in the literature about the effect of different doses of the effective drugs in the same experimental situation. However, on reviewing the experiments in which hyoscine has been used it became apparent that this drug had been used over a wide range of dose levels but in different situations, *e.g.* in aircraft, ships, and life-rafts and on swings. It had been shown to be effective in all of them, but the degree of protection obtained when related to the numbers who would have vomited without its protection (that is to the incidence of vomiting in the placebo group) was naturally very variable.

It was thought that it might be possible to arrive at some relationship between dose and response by the application of statistical methods. The results were analyzed by Mr. A. H. Gould, of the Army Medical Department, Stanmore, who corrected the figures relative to a standard incidence of vomiting in the placebo group, and by so doing was able to produce a relationship between dose and response for l-hyoscine, based on all previous experiments which we considered to be of reasonable design. The dose/response relationship so produced for l-hyoscine is shown in Fig. 2. Further analysis showed that the curves derived from data taken from experiments in aircraft, or in small ships were

parallel to this and did not differ from it or from one another by significant amounts.

This was the first time that a dose/response curve had been produced for any of the motion sickness drugs. Perhaps the most striking feature about it was the potency of L-hyoscine at doses much lower than those in general use. Previous workers had frequently given 1 mg. of the hydrobromide (*i.e.* = 0.7 mg of the base), and there was no doubt that at this dose level it afforded a very high degree of protection against motion of short duration. It was also evident that side effects due to its central depressant and peripheral parasympatholytic actions were also very troublesome at this dose. Little was known about its effects on motion sickness at lower dose-levels and we were inclined to doubt the somewhat high level of protection given on the curve. However we have since been able to confirm its potency at this level using a dose of 0.1 mg L-hyoscine base (or 0.15 mg of the hydrobromide) in a trial at Alverstoke where volunteers were again exposed to the motion of artificial waves. This trial was carried out with the support of the Survival at Sea Subcommittee of the RNPRC to whom the results have been reported in full (Brand, J. J., Colquhoun, W. P., Gould, A. H., McCance, R. A. and Perry, W. M., 1965). It is evident that the protection afforded at low dosage was at least as great as we suspected; the incidence of dry mouth was reduced to about half what it was at the higher dose, and there was no subjective blurred vision at the smaller dose level. This report is now being prepared for publication in the open press.

The compilation of such a curve has also been of great value in other respects. It now proved possible to gain some idea of the relative potencies of the effective drugs used in field trials. This was done by extrapolation from the hyoscine curve, using data derived from field trials of other effective drugs where an equivalent level of vomiting was found in the placebo group. This also gave us the opportunity to compare relative potencies against motion sickness to potencies as shown by *in vitro* tests of anti-acetylcholine and antihistamine activity, in case there was some correlation which might afford useful information about mechanism of action: these are set out in Table 4.

In all cases promethazine has been given a potency of 1.0 to make the figures more manageable. It now becomes apparent that L-hyoscine is by far the most active of all the drugs against motion sickness weight for weight, while meclozine has half the activity of promethazine, and diphenhydramine and cyclizine are approximately of equal effect. It is interesting to relate these potencies against motion sickness to other *in vitro* pharmacological actions. Many workers have won-

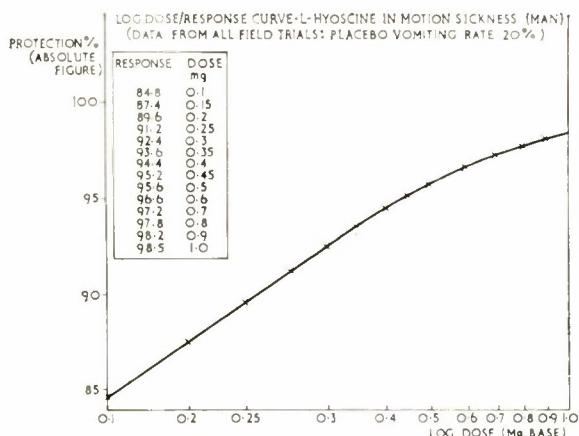


FIG. 2. A Dose/Response Curve for L-hyoscine.

dered whether a clue to the mode of action of motion sickness drugs lay in the fact that they all possessed some antihistamine or anti-acetylcholine activity. This seemed improbable insofar as peripheral anti-acetylcholine activity was concerned, in that many synthetic drugs which were developed and used for their peripheral spasmolytic properties were inactive against motion sickness.

When the relative activities of the drugs on tests of antihistamine or anti-acetylcholine potency are considered the discrepancies are obvious and it is apparent that in neither of these situations can their potency be taken as an index of anti-motion sickness effect. For example, L-hyoscine has very little antihistaminic activity although it is the most potent in the other tests. Chlorpromazine, although about 30 times as active as diphenhydramine against acetylcholine, and of equal antihistamic potency, is wholly inactive against motion sickness. Again cyclizine which is as active against motion sickness

TABLE 4. Relative Potencies.

Drug	Human Studies		<i>In Vitro</i> Tests	
	Motion Sickness	Vestibular Tests	V.s. Histamine	V.s. Acetylcholine
Hyoscine	60	(+)	0.0004	14.0
Promethazine	1.0	(+)	1.0	1.0
Meclozine	0.5	(+)	Nil	Nil
Diphenhydramine	0.3	(+)	0.1	0.9
Cyclizine	0.3	(+)	0.07	Nil
Mepyramine	Nil	Nil	2.4	0.003
Chlorpromazine	Nil	Nil	0.07	0.04
Phenindamine	Nil	Nil	0.3	0.03

1. All potency ratios are relative to promethazine.
2. Potencies v. motion sickness derived by extrapolation from dose/response curve for L-hyoscine.

and histamine as diphenhydramine, has no anti-acetylcholine action.

It is also most important to consider laboratory tests of motion sickness remedies in man. It would obviously be advantageous to have some method of assessing drugs in the laboratory so that one could then predict with confidence their activity under conditions of naturally occurring motion: this would be very useful in the evaluation of new drugs, avoid the many difficulties of arranging field trials, and perhaps give a clue as to their site and mechanism of action. Some of the methods which have been used are outlined in Table 1. The tests which have been used include the administration of emetic substances e.g. apomorphine (Isaacs 1954, 1956), and the assessment of the effects of drugs on labyrinthine function, using such devices as rotating platforms and parallel swings (Hulk and Jongkees 1948, De Wit 1953).

If tests which involve stimuli more specifically directed towards the labyrinth are considered, the position does look a little brighter, and since there is now little doubt that disorientating stimuli mediated through the labyrinth play the greatest part in the production of the motion sickness syndrome, there would seem to be some hope of evaluating motion sickness drugs by their effect on the measurable parameters of such stimulation under laboratory conditions. Turning tests were pioneered by Hulk and Jongkees in 1948 in Holland and applied more specifically to the problem of motion sickness by De Wit in 1953. Such methods fall naturally into two classes, (a) those involving the use of controlled angular decelerations by which the cupulae of the semi-circular canals are stimulated, and which give rise to measurable sensations of after-turning, or to nystagmus, and (b) those involving linear accelerative changes,

TABLE 5. Drugs Used in Motion Sickness.  
Methods of Study of Effects of Vestibular Stimulation in Man.

<b>A. Involving Stimulation of Cupulae—(semi-circular canals)</b>				
<i>Technique</i>	<i>Parameter Recorded</i>	<i>Method</i>	<i>Acceleration produced or simulated</i>	<i>Reference</i>
Caloric irrigation	Nystagmus	Objective (Electro-nystagmography)	Angular	Henriksson 1955
Rotating platform	Post-rotatory nystagmus	Objective: (E.N.G.)	Angular	Hulk and Jongkees 1948
Rotating platform	Post-rotatory sensation	Subjective: (timing with stop watch)	Angular	Hulk and Jongkees 1948 De Wit 1953
<b>B. Involving Stimulation of Otoliths (Utricles)</b>				
Parallel swing	Compensatory eye movements	Objective: (E.N.G.)	Linear Vertical	Philipszoon 1959

When drugs known to be effective against motion sickness were evaluated against apomorphine the results were disappointing. L-hyoscine at 0.5 mg (base) and promethazine (50 mg of Phenergan) had some effect in reducing vomiting, but chlorpromazine (Largactil 50 mg) was clearly much more powerful. However chlorpromazine has never been shown to be active against motion sickness in spite of its great clinical usefulness in dealing with vomiting from other causes. Some of these discrepancies may be explicable in a similar manner to those in the field trials, but the method does not appear to be promising as a possible screening technique. The explanation may well lie in a different site of action of the anti-emetic drugs.

which are thought to stimulate the otoliths: one way of studying the latter is by measuring compensatory eye movements. These methods are outlined in Table 5. None of these tests has yet been fully or systematically explored in testing motion sickness drugs, but there are certain clues, apart from *a priori* considerations, which make them appear to be of possible value in future research.

In 1948 Hulk and Jongkees described what they called the sensation and nystagmus Cupulogram. They stated that by subjecting men with normal labyrinthine function to a series of controlled decelerative stimuli on a rotating platform they could demonstrate a linear relationship between

the duration of the sensation of after-turning and the log stopping stimulus at any given rotational speed. This also appeared to be true for duration of nystagmus. These workers further defined normal slope values and thresholds of perception for such stimuli in a group of 50 subjects. These are shown in Figs. 3 and 4.

In 1953, De Wit used similar techniques, and suggested that labyrinthine sensitivity as shown by the slope of the sensation cupulogram appeared to afford some index of susceptibility to motion sickness, in that a small group of severely seasick individuals had steep cupulogram slopes while those of the relatively non-susceptible were flatter (Fig. 6).

He also suggested that diphenhydramine (Dramamine 100 mg) given orally two hours before a determination of the sensation cupulogram caused a shortening of after-sensation times, resulting in a flattening of the slope—*i.e.* a lessening of sensitivity to the effects of angular accelerations. Although these findings are open to criticism on many counts, particularly that any drug effect on this test may well have been obscured by habituation phenomena, they do provide a basis for further study.

In the parallel swing technique compensatory eye movements are evoked and these are held to be the result of otolith stimulation. This method has not been widely used in the study of drugs but may possibly be of value. It was used by Philipszoon in 1959 who found that normal compensatory eye movements were greatly reduced in amplitude after administration of cinnarizine. He also showed that this drug had a positive effect on the sensation and nystagmus eupulogram. It was shown to be active against motion sickness in a troopship trial at about the same time.

Thus there is a series of pointers which indicate that tests involving labyrinthine stimulation in the laboratory may be of value in the investigation of motion sickness drugs.

Tests involving rotational stimuli have been studied in much greater detail than those using parallel swings and are perhaps somewhat easier to quantify. Less attention has been paid to the effects of drugs on caloric tests but the results are encouraging. Perhaps the most important single fact is that all labyrinthine tests give positive results with drugs which are of proven efficacy against motion sickness. Unfortunately there are also indications that other drugs whose value is not clearly established may also modify such tests. Further research is obviously needed to evaluate the tests fully and to assess their possible use as laboratory screening techniques.

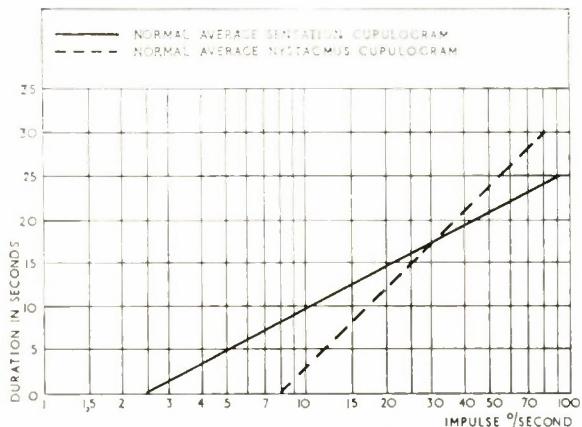
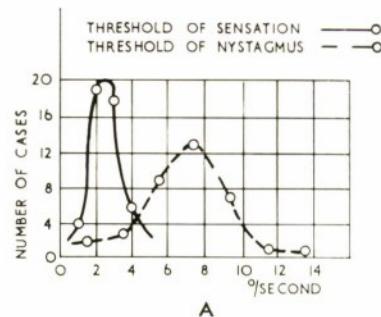


FIG. 3. Normal Sensation and Nystagmus Cupulogram (Hulk and Jongkees, 1948).



A

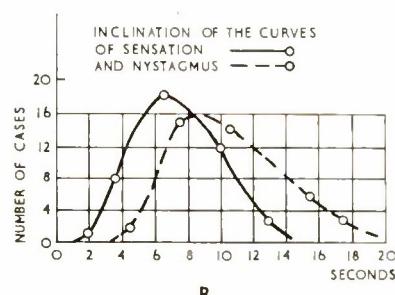


FIG. 4. Distribution of threshold and slope values (50 subjects).

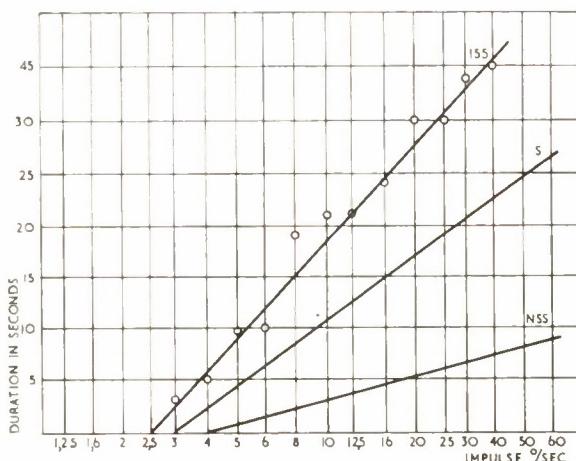


FIG. 5. Cupulograms in Sea-sick and Non-sea-sick (De Wit, 1953).

Space does not permit more than a brief discussion of studies which have been made using animal tests. The main experimental techniques which have been used have already been referred to. On the whole the results have been very disappointing in that it has not yet been possible to demonstrate a clear correlation between the effect of motion sickness drugs in any animal experiment and in field trials in man. There appears to be a very great species difference between the effects of drugs in man and the various experimental animals which have been used, and this was

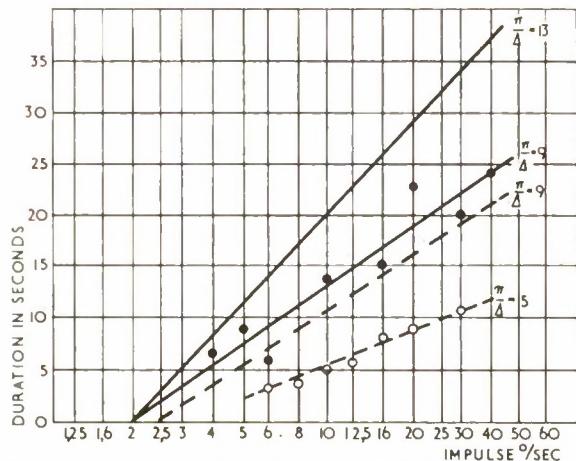


FIG. 6. Diphenhydramine (Dramamine) and the Sensation Cupulogram (De Wit, 1953).

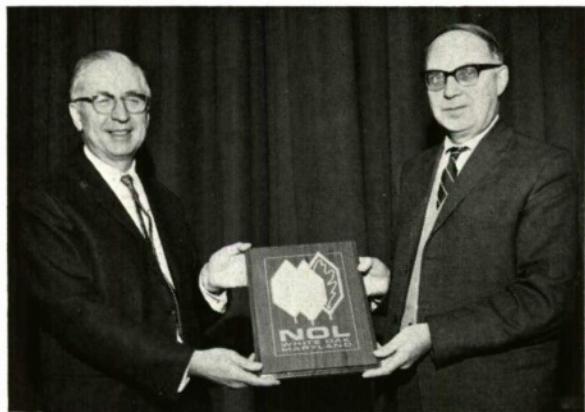
especially true when attempts were made to protect various species against the vomiting induced by chemical emetic agents. Perhaps the closest correlation between human and animal work was that obtained by Richards and his co-workers (1963). They showed that four of the established motion sickness drugs modified various parameters of calorically-induced nystagmus in the guinea pig. It is not yet clear, however, whether this property is shared by any drugs which are inactive against motion sickness in man and since there was no dose/response information for the effective drugs in the animal study it is not known whether their relative potency in producing this effect corresponds with that against motion sickness in man. Much further work is needed to clarify these points but the technique may be of possible value.

It remains true then, that there is, so far, no reliable method for the bio-assay of motion sickness drugs in animals and the value of laboratory tests based on labyrinthine stimulation in man is still uncertain. If a new drug is produced and there is any reason to believe that it might be of value in the prevention or treatment of motion sickness in man, it is still regrettably true that the only way of demonstrating its efficacy is by a properly conducted field trial in which due allowance is made for the variables already discussed. Potency against vomiting from other causes does not afford a reliable index of a possible protective action, and there is so far no known chemical or pharmacological test which can be relied upon to predict such protective activity. It might yet become possible to develop a laboratory method in man or animals based on the modification of responses to labyrinthine stimulation, and further research is contemplated to clarify this.

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*In order to mark the close association of the U.S. Naval Ordnance Laboratory with the Admiralty Research Laboratory, Mr. D. C. Hornig, (left) U.K. representative, on behalf of Dr. G. K. Hartmann, Director, N.O.L., presented, on 17th January 1968, a plaque bearing the insignia of N.O.L., to Mr. W. L. Borrows, Superintendent A.R.L.*

# THE ART OF DECISION MAKING

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H.M.S. Neptune

What is decision-making? Surely decisions are made after a logical application of known principles to known facts. Using this basic working definition it would appear that decisions are made as a result of a long, cool and detached analysis of a given situation, and are in fact a result of applied commonsense. Nothing could, in practice, be further from the truth. The key word in the premise above is "detached".

The ideal situation outlined is very largely how we think that we make decisions, based on how we know that we ought to make them. This approach could be put into a flow diagram shown in Fig. 1.

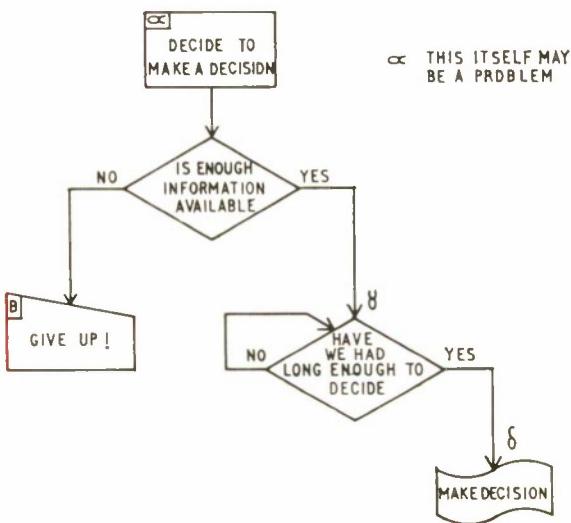


FIG. 1.

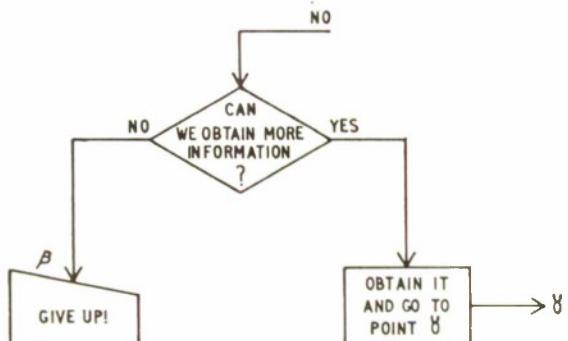


FIG. 2.

There are several ways in which this basic flow of constructive thought can be modified. Block  $\beta$ , for instance, instructs us to give up trying to make a decision if not enough information is available, and this block could be modified by replacing it with that in Fig. 2.

A further modification could be in the section starting at  $\delta$ —"Have we had long enough to make the decision?" The flow shown in Fig. 1 implies that unlimited time is available for the decision to be made and this itself may be impracticable. Thus the section of flow from point  $\delta$  may be re-drawn in Fig. 3.

The most important modification however raises the question of "detachment" posed in the basic definition. How often in everyday life is "non-detachment", as opposed to "involvement" a modifying factor just ahead of point  $\delta$ ? How

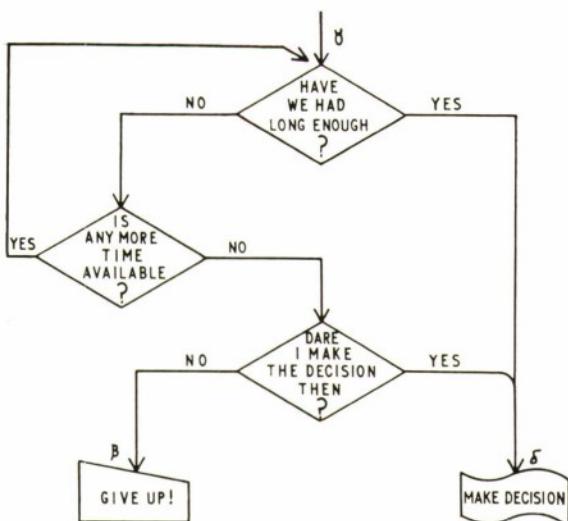


FIG. 3

often is the question of expediency brought in before the decision is made, when expediency was not one of the original items of informational data? It is a great pity that statistical data is so difficult to obtain on the number of decisions, logically and correctly arrived at, which are aborted due to non-relevant expediency. One could, I am convinced, quote several instances each day of just this sort of irrelevant step in the decision-making process, resulting in wrong decisions being made, or no decision being made. The flow posed so far, then, is as shown in Fig. 4.

The decision problem is compounded since each of the diamond-shaped boxes is, in itself, a decision box. Each decision box therefore contains, as a microprogram, this whole flow shown in Fig. 4, and the chances of aborting the whole decision, *i.e.* the original overall decision, multiply with each subsidiary decision box inserted in the flow. Also it will be apparent that the nearer one is to making the final decision, the more the time wasted increases when a possible "abort" decision box is inserted. There can be no complaint about expediency when expediency is one of the controlling parameters. It is when it is not that vast quantities

of time are wasted, and it is in an attempt to bring the expediency problem to people's attention that this article is written. If expediency is recognised as a control condition, the whole decision-making process can be aborted at the point of first entry to the "give-up" box without excessive waste of time. If it is not recognised as a control parameter, *i.e.* at the inception of the problem expediency is not considered to be a control parameter, then its casual insertion as a final decision box is grossly wasteful of decision time. Committee decisions which are over-ruled because they "might offend" are prime examples. Security regulations flouted because their application "might be inconvenient" are other examples.

The most important decision to make, at time zero, is the decision to stick by the decision made as a result of the application of the known principles. Involvement and motivational decisions can be tragic in their results in this computer age.

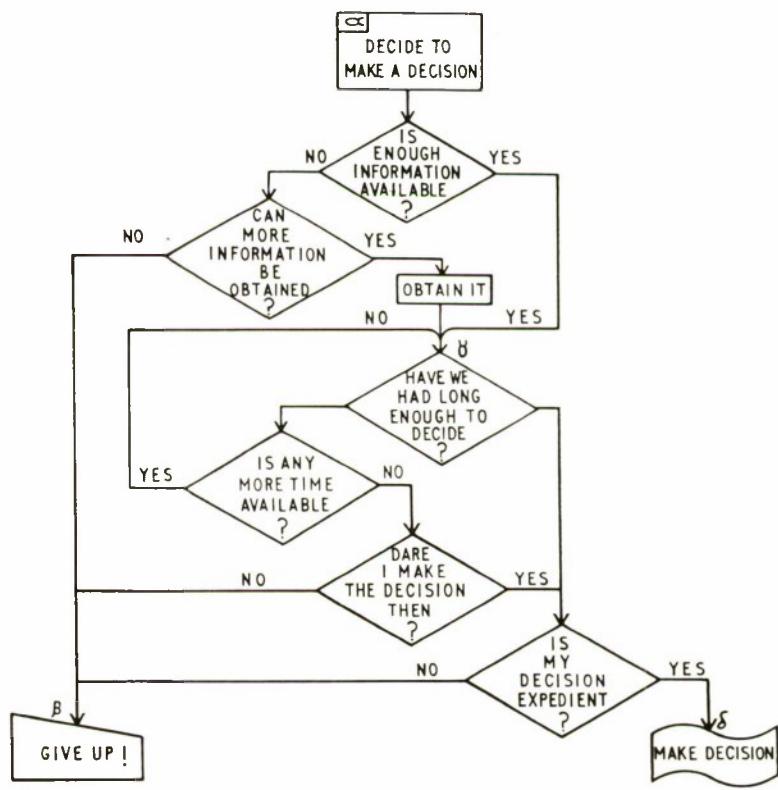


FIG. 4.

# THE POWER OF THE LOGISTIC FUNCTION

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In previous papers<sup>(1, 2)</sup> the use of the logistic function in assessing radar performance has been discussed, with reference to examples, and the theory of subjective probability proposed by Dr. I. J. Good has been featured. In this paper the use of the logistic by other workers will be considered and the function will be examined in the light of views held by Dr. Good, Professor Hogben, Dr. J. Berkson and other scientists. An example from Reference<sup>(1)</sup> will be referred to briefly to explain a choice of model and two fresh examples will be given to illustrate some further deliberations.

Frequent reference will be made to works by Dr. Good<sup>(3)</sup> and Professor Hogben<sup>(4)</sup>. Good's theory of probability has been called a landmark in subjective probability—the behaviouristic approach to statistical theory suggested by Hogben has not been enthusiastically received. Where some writers would advocate the use of two probabilities to cover objective and subjective phenomena, Good's view is that if a single theory covers both aspects, so much the better. He considers that in the last resort one must define one's concepts in terms of one's subjective experiences—the opposite view is that degrees of belief can be interpreted only by the methods of experimental psychology. Good also emphasizes that his theory is essentially practical.

On the other hand Hogben claims that if we are content to discuss the status of the calculus of probability as an instrument of research in terms of what goes on in the mind we have little hope of agreement—he insists on some acceptable distinction between knowing and believing. Behaviourism has no concern with structure or mechanism—the behaviourist is content to discuss probability in the vocabulary of events. One particular concern of Hogben's has been to remedy a widespread disposition among younger research workers not to examine the credentials of statistical principles used in their work.

We have seen already that the use of the logistic is compatible with both points of view and we shall see further the relevance of their views to the logistic and to its use in radar assessment work and in other fields. In the previous papers it has been shown that the function brings a desirable simplicity and unity to complex theoretical and practical problems and while being admirably suited to the gross description of phenomena without relation to its underlying structure, it never-

theless affords opportunities for analysis. The logistic has a satisfying philosophical rationale but to discuss this would be to enter largely controversial topics and discussion will be confined to more demonstrable matters.

The equations of the logistic are in their simplest form:—

$$Y = \frac{K}{1 + e^{a + bx}} \quad (i)$$

and

$$Y = \frac{K}{1 + e^{a + bx + cx^2}} \quad (ii)$$

Equation (i) is a symmetrical logistic, Equation (ii) is an asymmetrical, or skew, logistic, and K is the asymptotic upper limit to growth; for descriptions of population growth perhaps N is a more appropriate symbol. It is often very convenient to divide both sides of the equation by K (or N), thus obtaining a simpler function and an ordinate which ranges from 0 to 1—as does a probability distribution. The function has been called variously the "growth" function, the "autocatalytic curve" or sometimes the "Pearl-Reed" curve.

Pearl and Reed used the curve extensively for various biological purposes, all involving population growth, and they used it particularly to describe human population growth in various regions or countries. Their use of it to describe human population growth is not universally accepted. Some argue that although the logistic curve is appropriate enough to fruit flies in a bottle, its extension to human society is unwarranted. Human beings have, and exercise, the power of modifying their environment and rationally controlling their rate of reproduction. As we have seen in our applications of the logistic it has an underlying parametric structure which could sometimes reflect the influences of factors such as these upon the overall pattern, and their use of the logistic seems justifiable. For example, consider a case where the population of a large city over the years has been broken down into suburban growth and the growth of each suburb has been described by a logistic curve. Suppose, over the same period, there has been an influx of sub-populations into the various suburbs, whose attitudes to size of family and density of population are governed by religious or socio-economic pressures. It is very likely that the relationships between the parameters

of the logistics would reflect the presence of these influences. A similar method of analysis would be available in certain biological experiments where controlled conditions are difficult to achieve and the outcomes are often represented by logistic curves.

The logistic is frequently a better model in biological work than the normal curve. Hogben from the theoretical point of view, and Berkson<sup>(5)</sup> from the practical, have much to say about choice of model—Berkson particularly about the choice between logistic and normal. The logistic function is very close to the integrated normal curve (this was seen in<sup>(2)</sup>) and it is not limited to biological and economic data but has been applied to a wide range of physico-chemical phenomena. In fact Dr. Berkson has suggested that it may have a better theoretic basis than the integrated normal curve. Hogben constantly points out as a biologist the inadequacy of the normal curve as a model for biological phenomena and Good, also, points out that the normal curve is often a good fit to data except in the tails. From the radar field, a direct contrast between the fit of a logistic and the fit of the normal curve to experimental observations on sea clutter can be seen in Fig. 1. In this case the relevance of the logistic as a model can be understood clearly by regarding the sea clutter as a population of reflectors.

Returning briefly to the structure of the logistic function, it is possible by a transformation to obtain from the simple logistic the measure  $\log(p/q)$  or  $\log(\text{odds})$  in terms of a polynomial in the independent variable. Although the utility of this measure was arrived at independently<sup>(1)</sup> during a search for approximations, Good, Berkson and Fisher had also previously utilized it. Good calls the measure the "plausibility". Berkson calls the corresponding experimental quantities "logits" and Fisher uses it in his "z" transformation. Hogben also favours the expression of probabilities in terms of "odds".

Berkson, justifying his use of "logits" rather than "probits" (the corresponding quantity based on the normal curve), says that in spite of earnest prayer and the greatest desire to adhere to proper statistical behaviour he could not see why the method of maximum likelihood is to be preferred to other methods, particularly the method of least squares. Berkson collected as many examples as he could find, within the field of application, of data in which the observations were sufficiently numerous and for which the integrated normal curve had been used already. The logistic function was applied to the same data and the results were compared. On the basis of the comparative  $\chi^2$  values either the results were practically the same or there was an advantage in favour

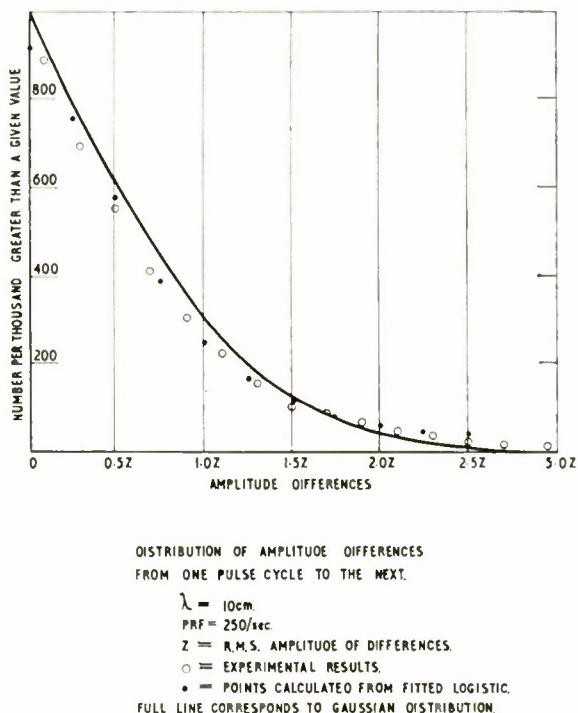


FIG. 1. Differences between normal curve and logistic in fit to observed data on sea clutter.  
(From Ross—Analysis of present information on the scattering of radar signals by the Sea—Pt. I.)

of the logistic. In no instance did the normal curve appear the better of the two. This illustrates very well several points stressed by Hogben—that several models can exist and that one's choice of model can be governed by one's approach; that the normal curve does not always offer the best model and that research workers are well advised to consider the principles underlying their choice of model.

In Reference<sup>(1)</sup> an example was given of the use of logistic curves to approximate to complex mathematical formulae representing theoretical distributions of probability of paint. Similarly in Reference<sup>(2)</sup> logistics were used to represent theoretical distributions of probability of detection. Unlike the cases of sea clutter, where the logistic as a model clearly relates to populations of individual reflectors, no explanation of the logistic as a model for these probability distributions could be offered. One way to understanding lies in the study of the transport properties of solids—their capacity to conduct heat and electricity. Referring to J. M. Ziman's lucid and evocative book on this subject<sup>(6)</sup>, it can be seen that the Fermi-Dirac distribution function

$$f^o(\epsilon k) = \frac{1}{\exp\{(\epsilon k - \xi)/kT\} + 1}$$

is in the form of a symmetrical logistic. This function is used in the description of the occupation of the energy levels by electrons in the thermal layer of a proper metal. It can be seen therefore that by using the logistic for the approximation of the theoretical probability distribution we were in effect replacing a complex mathematical model by a simple physical one. In the first example a skew logistic gave a good fit over the whole range of  $P$  but the approximation using a symmetrical logistic broke down for large values of  $P$  (or close ranges of the target)—it is noteworthy that a similar degeneration occurs with the Fermi-Dirac distribution; the function becomes the Boltzman distribution—as if the electrons made a classical gas. The Boltzman distribution is of form

$$f^o(\epsilon) = \frac{1}{\exp\{(\epsilon - \xi)/kT\}}$$

and it can be seen that its form is similar to that of the Fermi-Dirac function except that a parameter previously of value +1 has become zero. Referring again to Ziman's book, the Bose-Einstein distribution (see footnote) is also in the logistic form. This function is used to describe the transport of heat through solids in terms of phonons (phonons are quanta of the lattice vibrational field analogous to photons of the electromagnetic field) and in this case the changing parameter has the value  $-1$ ! There is, therefore, a pattern to be seen in the formulae used to represent the different particle statistics. Can this pattern be related to any changing circumstances of the physical events being described?

If the logistic is considered in its general form  $Y = 1/a(1 + be^x)$  it can be seen at once that the Fermi-Dirac and Bose-Einstein functions may be put into this form but the Boltzman cannot. The parameter  $a$  can now be related to  $N$  (from the logistic in its simplest form) and this is known to represent the upper limit of population growth. To consider all possible values of  $N$  it becomes necessary to introduce the idea of the "transfinite".

The brilliant mathematician G. Cantor demonstrated the existence of two distinct orders of infinity. The lower order infinity includes all integers and rational fractions which are "denumerable". The higher order infinity includes all real numbers—it is the "continuum" and is not denumerable. Cantor showed this by a special counting technique. He also showed that there existed still greater orders of infinity. This series of "transfinite" numbers he called the "Alephs". Thus Aleph nought is the denumerable infinity of the integers, Aleph one is the non-denumerable

infinity of all geometric points, Aleph two includes all geometric curves—no one has yet been able to suggest what Aleph three represents!

If we count our populations of particles in these terms, *i.e.* we express  $N$  in terms of transfinite numbers, we have a direct correspondence between  $a$  and  $N$ , shown in Fig. 2. Here the change of sign of  $a$  indicates the operation of transfer from finite to transfinite. Counting in transfinite numbers serves several purposes:

- (a) it is consistent with models of balls in cells;
- (b) it emphasizes the operational aspect of the transition from finite to transfinite;
- (c) it introduces Aleph two and the higher Alephs which have some philosophical implications;
- (d) it has relevance to theories developed explain the latest experimental results on gravitation and relativity;
- (e) it indicates a way of approach to particle physics which is consistent with current views of elementary particles as simply "abstract attributes concealed in the symmetries of transcendental mathematical spaces".

Each of these points will be expanded in turn.

- (a) The drawing of a parallel between the Bose-Einstein statistics and the transfinite is consistent with the model of an unrestricted number of balls being allowed to occupy a cell. Cantor's diagonal counting procedure will show that given an infinitude of cells and balls the number of possible populations is non-denumerable. The concept of dividing

#### Footnote

There are three kinds of statistics commonly used in particle physics to describe the behaviour of particles. These are Fermi-Dirac, Maxwell Boltzman and Bose-Einstein statistics. Fermi-Dirac statistics describe the behaviour of electrons, protons and neutrons; Bose-Einstein the statistics the behaviour of photons, nuclei and atoms with equal numbers of elementary particles. Maxwell-Boltzman statistics are not wholly satisfactory for particles of any sort. Customarily space is conceived as a grid of cells to each of which one or more balls can be allocated. The statistical models then describe the allocation of balls into cells under the postulates, in order:-

- (a) the balls are indistinguishable, and one cell can only accommodate one ball;
- (b) the balls are indistinguishable, and there is no restriction on the number per cell;
- (c) the balls are distinguishable, and there is no restriction on the number allocated to any one cell.

The relevance to solid state transport theory is clear. In the Fermi-Dirac distribution, concerned with the conduction of electricity, the exclusion principle prevents more than one electron occupying the same state of momentum and spin and in the Bose-Einstein, concerned with the conduction of heat, any number of phonons—"Bose-Einstein" particles—may go into any given energy level.

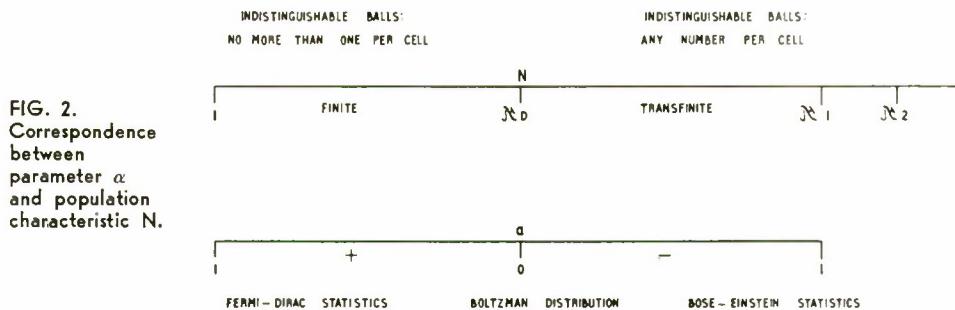


FIG. 2.  
Correspondence  
between  
parameter  $\alpha$   
and population  
characteristic  $N$ .

space (also time) into cells has been suggested by many—notably Arthur March who proposed a system of geometry based on the concept of the existence of a minimum length, space having the characteristic of a cell-like structure. Alternatively an infinite number of particles may be considered—each particle being composite and made up from truly fundamental particles popularly known as “quarks”. Such an idea was suggested at last year’s high-energy physics conference at Berkeley in California. There are several points arising at this conference which are worthy of mention.

A scheme for grouping all known strongly interacting particles into discrete families of particles is provided by plotting Regge trajectories. It was reported at the conference that by considering the extension of trajectories to the NEGATIVE-mass side of the abscissa it has become possible to predict a hitherto inexplicable experimental observation (a region of negative effective mass is also found in transport theory, where the concept of a hole in the energy band has been introduced to deal with it). If all the known nuclear particles seemingly lie on Regge trajectories it could be concluded that all the known particles are composite—that is made up of other particles.

An over-simplified way to understand this conclusion comes from noticing that the mass or rest-energy of the members of a family of particles making up a trajectory increases with each increase in spin number. One would expect the energy of a system to increase with spin only if the system has some finite dimension or structure which can “rotate” and hence possess rotational energy. Discussion on these topics moved a well known theoretician G. F. Chew to observe that we are probably soon going to conclude that the number of nuclear particles is infinite. The picture of matter at its most fundamental level, then, would be of

an infinite set of particles, each of which is composite.

- (b) The change of sign accompanying the operation of transfer from the finite to the transfinite in our example, and from positive mass to negative mass with Regge trajectories (and in transport theory), deserves further attention. Gunther<sup>(7)</sup> and Campbell have shown, by the methods of symbolic logic, that a technique which eliminates the quantization of matter is logically possible and as a consequence the underlying mathematical theory is changed from denumerable arithmetics to transfinite Cantorian numbers. The technique involves adding to the three parameters recognized to-day—the objective parameter, Matter; the dimensional parameter, Space; the relational parameter, Time—a fourth cosmical component, the operational parameter, P. If Dr. Good would prefer to call it a subjective component—who would disagree?
- (c) This leads to a brief mention of Aleph two and the other Alephs. With their introduction comes the implication that in the realm of the transfinite subjective probability comes into its own. One can visualize vast numbers of sets of relationships differing only minutely, where the outcome of a trial is governed by the locality in which the set of events takes place; all other identifiable circumstances appearing the same. This concept might bring cheer into the life of these statisticians belonging to the frequency school who cannot accept Bayes’s postulate. These say that “it is asking too much of the universe” for states of events corresponding to various q’s (hypotheses) to be distributed with equal frequency in some population from which the actual q has arisen, if Bayes’s postulate is to be applied. In this respect it is not without significance that the symmetrical logistic gives a straight line in terms of plausibility and consequently for equally spaced points along the abscissa there is a constant increase in the weight of evidence<sup>(3)</sup>.

Furthermore much of the usefulness of the logistic lies in circumstances where there is no prior knowledge of the situation.

- (d) R. H. Dicke, of Princeton University, recently in the news for his experiment demonstrating the oblateness of the sun, proposes a theory to explain gravitational phenomena whereby each point in space has a specific physical quality to which a single value can be assigned. In essence this is not a novel concept—it has been suggested by others.

These ideas run parallel to those emerging in particle physics where it is being thought that "the only permanent elements of nature are not particles but certain of their abstract attributes lying concealed in the transcendental symmetries of fictitious mathematical spaces. The Harmony in nature is now seen in particle theory as synonymous with abstruse symmetries incalculably more sophisticated than the obvious geometrical patterns trapped by the 'Real' space and time of man's apperceptions"—<sup>(o)</sup>.

- (e) Lastly to consider particle physics. The latest views on this, as evidenced by reports from the Berkeley conference, suggest that the concept of large populations of particles is consistent with descriptions by logistics of observed phenomena. Alternatively, they suggest that the idea of the phenomena as reflecting characteristics of mathematical space is compatible with the idea of Cantor's transfinite numbers, to which the logistics can lead. The suggestion has been made by H. Bethe that more powerful mathematical tools are needed to tackle the problem of the nucleus. This was taken up by Gunther and Campbell who proffered Cantor's theory of non-denumerable sets as a possible key to the problem. These ideas fit in very well with Ziman's opinions. He says that in certain circumstances we must replace the individual article by a collective model. It seems likely, therefore, that there is further use for the logistic in this field.

Ziman also says "the main conclusion to be drawn from the general theory of lattice dynamics is that its results are impossibly complicated in detail." W. O. Lock, author of "High-Energy Nuclear Physics"<sup>(8)</sup> says much the same thing of certain particle collisions—that they can only be described in phenomenological terms. It has been shown that much of the power of the logistic lies in its reduction of complex situations to simple ones and its capacity for describing events about which little or nothing is known.

To illustrate these points a logistic was fitted to the first set of experimental data which could be found—selected at random from the library shelves on nuclear physics. The data, the theoretical curve fitted by the experimenters and the fitted logistic are shown in Fig. 3. It is noteworthy that over the central parts of the distribution the logistic and the theoretical curve coincide and that in the tails the logistic gives a better fit. This example is in fact taken from Lock's book.

In conclusion it is suggested that by the fitting of this curve the power of the logistic was again reaffirmed, for one of Hogben's criteria for a good model is that as well as describing observed events it should also point to further unsuspected regularities of nature!

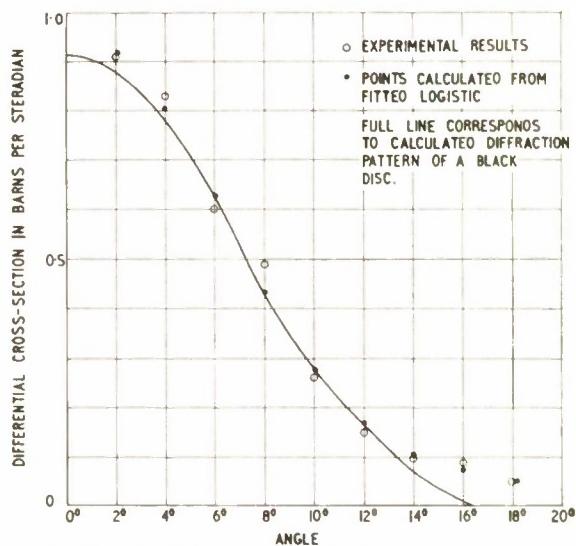


FIG. 3. The differential cross-section for 350 M<sub>e</sub>V protons scattered from carbon  
(From Lock—High Energy Nuclear Physics)

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# RECEPTION OF SIGNALS OF LARGE TIME-BANDWIDTH PRODUCT VIA A VARYING PROPAGATION PATH

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## SUMMARY

*Any band-spread signalling system is vulnerable to variations in the generalized signal path occurring within the time, frequency and aperture spread of the signal. However, a system's vulnerability to such changes depends on the nature of the modulation. This dependence is indicated in arguments using the concepts of the "ambiguity function" and frequency-time resolution quantum. It is then derived and discussed more fully, without depending on an intimate familiarity with these concepts. The discussion is also extended to tolerances on angular rates or changes within the near field of the transmitting or receiving array. The choice of modulation waveforms and of partially coherent receiving filters, to reduce vulnerability to any or all of these changes, is briefly considered. Most of the considerations referring to varying paths are also applicable—mutatis mutandis—to multiple simultaneous paths, and the relations between these two phenomena are briefly discussed.*

## Introduction

Many systems for information gathering or transmission require to use relatively long signals, in order to transmit the required energy within given limitations on peak power, or possibly in order to permit the accurate determination of the received spectrum (or Doppler shift). On the other hand, many systems require the signals to cover a wide bandwidth, for instance in order to provide a high time resolution of received signals, or a high discrimination against signals reflected from unwanted scatterers or arriving via undesired propagation modes. These requirements of long duration and wide bandwidth can be combined by deliberately spreading the signal in the frequency/time plane, prior to transmission, and re-compressing it on reception, as described below.

Ideally, an initially short pulse may be spread out in time, by a tapped delay line, into a number of consecutive pulses, which can be independently controlled in amplitude and/or phase. An inverse network can then restore essentially the original pulse. Similarly, a series of mixers can transpose the frequency spectrum of a simple "burst", i.e. pulse, of CW into a number of independent parallel spectra, which may then be independently controlled in amplitude and/or phase. Again an inverse network can restore essentially the initial signal, and the same is true for simultaneous spreading in the time and frequency dimension. See Fig. 1.

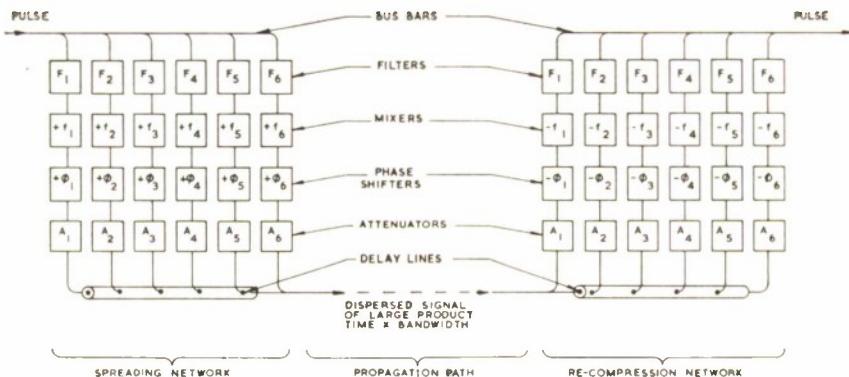


FIG. 1. Simple schematic of signal spreading and re-compression.

The sequence in which *interchangeable* transformations take place is by definition immaterial. Subject to this condition, a propagation path may be inserted between the spreading and recompression networks without altering their joint effect on the overall circuit. The interchangeable transformations need not always be "linear": If harmonics or inter-modulation products fall outside the pass-band of the system, or if they are removed by an inverse non-linear element before they become relevant, a square-law, exponential or other power-series amplifier (or other non-linear circuit element with a single-valued input-output relationship) may also be inserted in a sequence of transfer networks. (Care is however required lest the sequence of such apparently reciprocal signal transformations has a deleterious effect on the output signal/noise ratio.)

On the other hand, the effects of a limiter can be critically dependent on any preceding amplitude transformations. Similarly, the effects of a frequency-selective filter depend on any preceding frequency transformations, including those due to the Doppler effect, and the effects of any time selection or transformation can depend critically on preceding time transpositions. In particular, any spreading of the signal in time and/or frequency will increase the limits of time and frequency within which changes in system parameters will affect the eventual output after recompression.

During the operation of a practical system, the propagation path may change due to:—

- (i) changes in the characteristics of the medium,
- (ii) changes in the homogeneity of the medium,
- (iii) movement of inhomogeneities in the medium,
- (iv) changes in the location or orientation of:—  
the transmitting transducer or aerial,  
the receiving transducer or aerial,  
intermediate specular or irregular reflectors,

(v) movement of the effective reflecting "point" on an irregular reflector,

(vi) various combinations of effects (i) to (v) above.

*Systematic* changes in position or velocity may affect the choice of receiving filter in which matched reception takes place, and may complicate its design. However, the quality of the resulting match is then only affected by the departure from this matched condition, within the duration of the signal from one point target (or one "bit" of transmitted information). In principle it is of course possible to design an array of filters or correlators to observe, independently, each possible and resolvable signal location in time and (if relevant) in Doppler, and *each discrete pattern of distortion that could be associated with this*. (The number of independent observations of this type in fact cannot exceed the bandwidth—observation time product of the receiving system, i.e. all others can in principle be synthesized or computed from these). However, such an array of filters or correlators, matched to a range of potential variations of the propagation path, can be helpful only if the probability of noise alone producing a "false alarm" output, matching any one of the distortion patterns catered for, is small. In practice, well before this "false alarm" limit is reached, the cost and complexity of the system are likely to become prohibitively large.

Hence the number of patterns covered by the range of such matched filters is likely to be very small, compared with the number of patterns the receiver is capable of passing. However, even when purely random distortions are excluded, the number of such potential patterns increases highly super-proportionally with both the duration and the bandwidth over which coherence has to be maintained (i.e. the two-dimensional limits over which time or frequency dispersion has to be avoided). We are therefore concerned with making

the best use of a limited amount of "hardware" available for such generalized "matched filters".

### General

A large time-bandwidth product implies that a single element of information is represented by a large number of signal elements, separable on the frequency/time plane. Each such signal element is equivalent to one cycle at its "instantaneous bandwidth". A "matched filter" must transpose all these elements in time, phase and possibly frequency, to permit their phase-coherent addition. (It should also scale them in amplitude to optimize the resulting signal/noise ratio.)

Any progressive departure from the matched phase, over the total signal duration, leads to a corresponding reduction in the matched-filter output. (With signal elements of equal "weight" and a linear phase-shift of  $2\theta$  over the duration of the signal, the loss factor is  $\sin^2\theta/\theta^2$ .) The time "available" for troublesome phase-distortions, not covered by the filter, to develop is clearly the signal duration  $T$ . More generally, the signal must retain the relative amplitude and phase pattern, to which the filter is matched, over its duration  $T$  and bandwidth  $B$ . A wide bandwidth implies a fine resolution in time (*i.e.* path-length), and a long duration provides increased opportunities for this path-length (or some other characteristic) to change sufficiently to spread the signal over several resolution quanta.

The response of a matched filter may be plotted as an amplitude, which is a function of the two-dimensional displacement of the apparent signal source from the matched position on the time/Doppler plane. This is the "ambiguity function", and it normally takes the form of a "main lobe", representing full response at the matched position, surrounded by a pattern of low-amplitude "side lobes".

Any modification, diversification or variation of the transmission path can then be defined as an equivalent smearing of the single-point target location on the range/Doppler (*i.e.* range-rate) plane into a two-dimensional "target function". Subject to appropriate amplitude weighting, the proportion of the received signal power accepted by a correlation detector will then correspond to the proportion of the target function that falls within the detector's "ambiguity function" on the range/Doppler plane. (This statement refers to the "instantaneous" target function, if the target position itself varies within the echo duration.)

If the "smearing" takes the form of discrete multiple propagation paths, differing by more than the width of the ambiguity function main lobe, the received power is dispersed between multiple, pseudo-independent received signals.

Any progressive increase in range must clearly be associated with a positive mean range-rate and vice versa for a progressive decrease in range. Thus an ambiguity function in which range and range-rate are positively correlated is likely to be more tolerant of such changes in the propagation path.

In wave-forms producing this type of ambiguity function, the signal "cycle-time" (*i.e.* interval between positive going zero crossings) must be positively correlated with time within the wave-form, so that Doppler time expansion shall correlate with overall time expansion—*i.e.* increase in path length. This implies a downward frequency sweep.

The volume under the ambiguity function corresponds to the (normalized) total power incident upon the matched filter, and this is always unity. With a smooth progressive change of wave-form and power (which can be conveniently achieved with a quasi-linear frequency modulation and quasi-Gaussian amplitude modulation) there will be no significant side lobes, and hence the main lobe, (of unit amplitude) will occupy roughly unit area on the ambiguity (time/Doppler) plane. With increasing departure from such smooth variation of modulation, the output of a matched filter becomes more sensitive to small misalignments in timing (range) or in Doppler frequency. Hence the main lobe of the ambiguity function is reduced in area (and the proportion of the signal energy going into side lobes is increased).

A quasi-random "noise" signal, of bandwidth  $F$  and duration  $T$ , covering  $FT=N$  frequency-time quanta, has a lobe width of  $1/T$  in the frequency dimension and  $1/F$  in the time (range) dimension of its ambiguity function. Thus its main lobe covers only  $1/N$  of a "quantum" on the range (time)/Doppler plane, and this defines the permissible spread of the target function due to changes in the system during the integration period of the matched filter (or due to overlapping multiple paths, combining in a single output). See Fig. 2. The maximum permissible spread, defined by the size of the main lobe is thus less than one "quantum".

Thus we obtain the apparent "resolution" due to a main lobe of the ambiguity function, of unit amplitude, occupying an "area" of  $1/N$  of a quantum on the frequency-time plane. The volume of this main lobe represents the proportion of the received power, from a target in the main-lobe location that would in fact emerge from a filter matched to that location. Hence this signal power is only approximately  $1/N$  of the power received jointly from the  $N^2$  side lobes. In fact we can obtain the accuracy represented by this lobe width, but only if the distribution of targets is such that the power received from the signal lobe is more

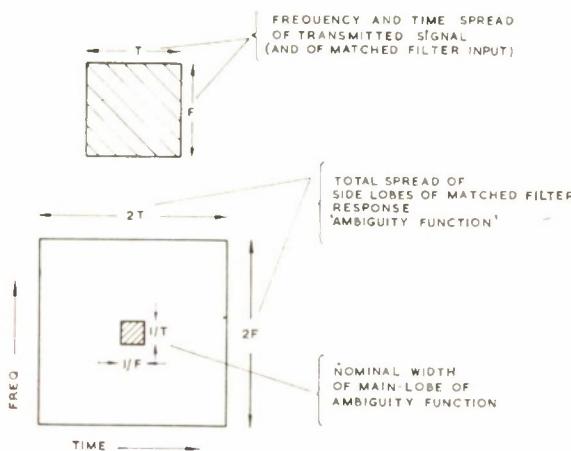


FIG. 2. Ambiguity function of a random spread spectrum signal.

than  $N$  times the power received from the average background lobe of the ambiguity function (*i.e.* if the signal power exceeds the background power from a typical quantum of space on the ambiguity plane).

Thus the average density of equal targets must be less than one per quantum, to resolve the targets, but subject to this limit, a pair of targets can be resolved if they are separated by one lobe width.

The tolerances on changes in the propagation path or medium, for two limiting wave-forms, are discussed in more detail below.

#### Doppler Tolerances for Linear F.M. and Pseudo-Random Noise

Consider a linear frequency sweep of  $F$  Hertz in  $T$  seconds. This sweep will be within the passband of a receiver of bandwidth  $B$  ( $B < F$ ) for time

$$t_1 = (B/F) T,$$

if the time of sweeping through the bandwidth is the dominant factor. On the other hand, the sweep may pass through the receiver passband very rapidly, giving an output for the transient response time

$$t_2 = 1/B.$$

See Fig. 3. When these two conditions coincide, the response time is

$$t = t_1 = t_2 = \sqrt{T/F}$$

the "instantaneous" bandwidth is then

$$B = \sqrt{F/T},$$

the square root of the frequency-deviation rate, and the joint resolution in time and frequency is

$$Bt = 1,$$

*i.e.* one quantum (unit area) on the frequency-time-plane.

The total signal could thus be resolved into  $\sqrt{FT} = n$  independent quanta. A matched filter of  $n$  frequency-selective networks and  $n$  delay networks could be used to bring these into coincidence. The resultant signal would then have a total bandwidth of  $F$  and overall duration of  $T/n$ . However the  $n$  frequency components, spaced one from the next by  $n/T$  cycles/sec, would remain in phase for only  $1/n$  of this time. Hence the resultant signal would give a "main-lobe" response for  $T/n^2 = T/FT = 1/F$  seconds, corresponding to a properly reconstituted short pulse. (The same result would of course be obtained with a matched continuously dispersive delay line.) Similarly an f.m. correlator would give a C.W. output of duration  $T$  and bandwidth  $1/T$ . The frequency modulation would move it outside this passband if it were displaced, in time, by

$$t = \left( \frac{1/T}{F} \right) T = 1/F.$$

Clearly all these variants of a filter can discriminate signals differing in Doppler by  $F$  or in effective timing by  $1/F$ .\* Thus the ambiguity function main lobe in this case occupies one quantum on the time/Doppler plane. Hence the area of the side lobes and proportion of the signal power going into side lobes should be relatively small (and in the absence of sharp amplitude discontinuities in the signal, the amplitude of the side lobes should also be small). This is the result of a modulation representing a smooth progressive time dis-

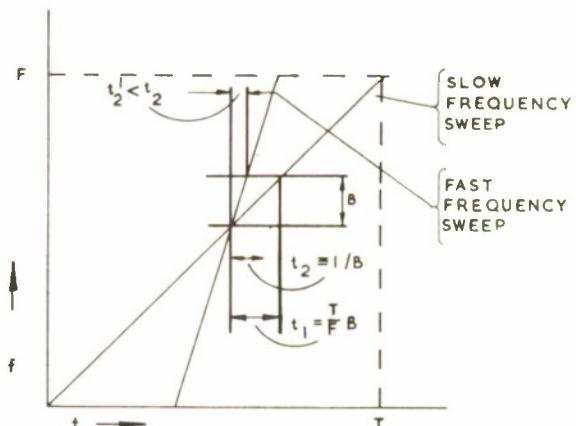


FIG. 3. Duration of transient due to frequency sweep.

\* "effective timing" defines the combined effects of timing and Doppler shift of the input signal on the time of occurrence of the filter output pulse; Doppler resolution is the frequency shift which would preclude any output from the filter.

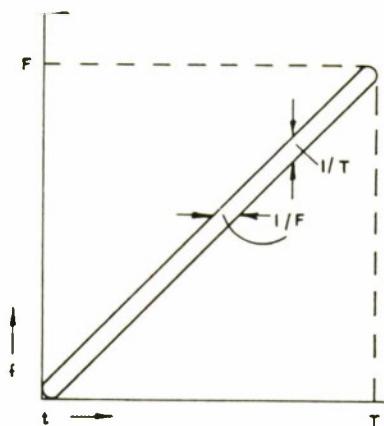


FIG. 4. Ambiguity function due to sweep of frequency  $F$  in time  $T$ .

persion of the spectral components of a pulse by progressively sweeping through its spectrum, avoiding any sharp discontinuities.

The dispersion of the signal spectrum in time must however lead to a corresponding dispersal of the acceptance pattern. Hence the corresponding ambiguity function is a diagonal strip across the time/Doppler plane spanning  $F$  cycles per second of Doppler and  $T$  seconds of time. Since this strip has unit area (as shown above), its thickness must be  $1/T$  Hertz in Doppler and  $1/F$  seconds in time. See Fig. 4.

In fact Fig. 4 implies the assumption that the centre frequency is large compared with the frequency sweep (and compared with any likely Doppler shift). Where these conditions are not satisfied, the linear frequency sweep may be regarded as composed of several "Doppler-invariant" sections, in each of which the cycle time (between positive-going zero crossings) varies linearly with time—*i.e.* hyperbolic frequency modulation. The ambiguity functions due to these individual sections would differ in slope, so that their combined result is a "double fan". Furthermore their individual lengths will be less, due to their reduced time and frequency span. Thus the diagonal of the "double fan" is less than the length of the single "strip" ambiguity function shown in Fig. 4, as is indeed required to maintain the unit volume under the ambiguity function.

Consider now a signal in a region of the frequency/time plane bounded by a frequency interval  $F$  and a time interval  $T$ . Then, by the quantum limitation on measurement,  $FT \geq 1$ . In fact, let  $FT \gg 1$ . See Fig. 5. Then a time interval less than  $T$  may contain a part of the signal spanning its full frequency spectrum. Similarly, power within a limited part of the bandwidth  $F$  may be present for the whole of the signal duration. More generally, less than the full

frequency/time pattern of the signal may be sufficient to define the span of the signal on two separate axes on that plane. (The signal components, suitably transposed, could then generate several quite independent full bandwidth pulses or full-duration C.W. signals.)

The signal pattern on the frequency-time plane could then be divided into a number of constituent patterns, each occupying unit area on this "signal plane". These constituent signals could each produce an ambiguity function of unit area on the time/Doppler plane. Since all refer to a common real target position, these ambiguity functions must clearly overlap, and the vector addition of the corresponding constituent signals would define a composite, resultant ambiguity function whose side lobes cover the total area defined by the lobes of any of the constituent functions, and whose main lobe is restricted to the area (less than one "quantum") common in signal phase and range/Doppler space to all the constituent main lobes. See Figs. 6 and 9.

The signals emerging from filters matched to the individual constituent signals may then be regarded as inputs to a further matched filter, and their normalized vector addition will define the lobe structure of the overall ambiguity function. The constituent ambiguity functions will have main lobes of (approximately) unit area, and the in-phase addition of the corresponding signals will produce a combined main-lobe peak whose area cannot exceed the area common to all the constituent main lobes. (Variations in relative phase between constituent main-lobe signals may narrow the overall main lobe further.)

Hence, if the constituent ambiguity functions are ellipses of various inclinations (positive, negative, horizontal or vertical) and various aspect ratios, the resultant must also be skew-symmetrical—*i.e.* identical with itself turned through  $180^\circ$ .

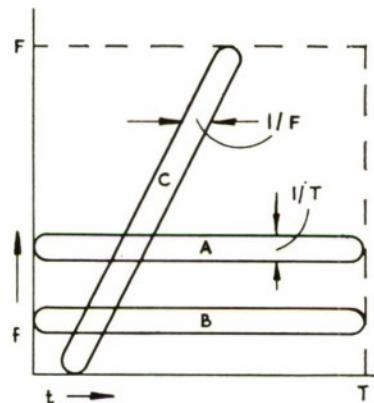


FIG. 5. Modulation pattern of 3 quanta within space  $F \times T$  of 11 quanta.

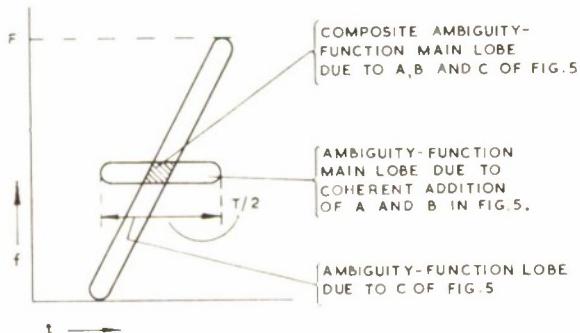
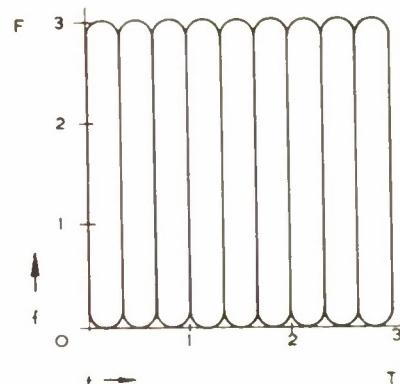


FIG. 6. Generation of Composite ambiguity function with main lobe less than one quantum.

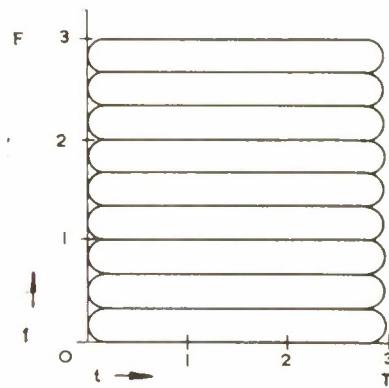
This way of considering the formation of ambiguity functions may be helpful in the choice of modulation wave-forms and signal-processing systems meeting various specific requirements arising, say from a non-uniform distribution of noise, interference, clutter or reverberation.

A randomly modulated signal of duration T and bandwidth F occupies the full rectangle of  $FT$  on the frequency-time plane. This corresponds to  $FT$  "quanta", which can be defined, e.g. by splitting this rectangle into  $\sqrt{FT}$  rows by  $\sqrt{FT}$  columns. The rows then have a width of  $\sqrt{F}/T$  each, in the frequency dimension, and the columns have a width of  $\sqrt{T}/F$  each, in the time dimension. The analysis above shows that a linear frequency sweep is equivalent to a single diagonal of this rectangle. This diagonal may be built up of some of the quanta, but each quantum is then the sole occupant of its row and column. Linear frequency modulation provides no scope for altering the aspect ratio of the resolution quanta ( $\sqrt{F}/T$  in the frequency dimension by  $\sqrt{T}/F$  in the time dimension). With random modulation, however, they are infinitely alterable, subject to the boundary conditions that the limiting time resolution of the system is  $1/F$  (with the quanta each spanning the full bandwidth of the signal) and its limiting frequency resolution is  $1/T$  (with the quanta each spanning the full signal duration). See Figs. 7 and 8.

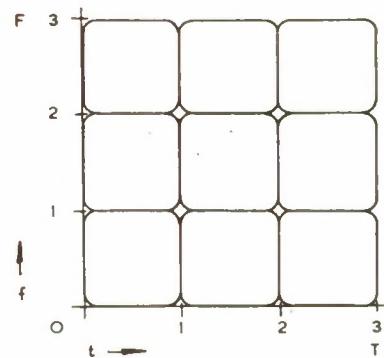
As discussed above, the full-occupancy "pseudorandom noise" signal would permit the employment of several independent filters, matched to independent parts of the received signal. The final resulting ambiguity function must then have its main lobe at the intersection of the constituent ambiguity functions. Clearly we can form such functions for C.W. of duration T or pulses of bandwidth F, or for both positive- and negative-going f.m. sweeps spanning T and F. Hence the intersection defining the main lobe of the resulting



(a) Time Resolution =  $1/F$



(b) Frequency Resolution  $1/T$



(c) Time and frequency resolution = 1

FIG. 7. Three ways of analyzing a signal occupying 9 quanta of frequency/time space.

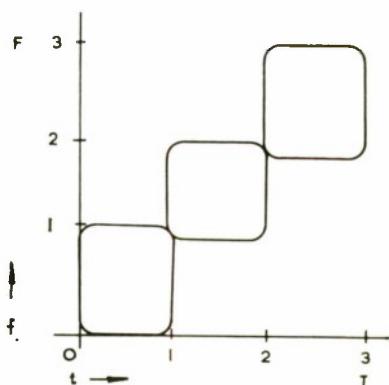


FIG. 8. Linear FM in 3 quanta. A coherent filter can reduce this to a single thin diagonal quantum.

ambiguity function must be restricted to duration  $1/F$  and Doppler width  $1/T$ , as already inferred earlier. Comparing this with the ambiguity function of f.m., it will be noted that the latter constitutes a "ridge", equivalent to a diagonal line of FT of the sharp, pseudo-random-noise ambiguity peaks, placed side-by-side. See Fig. 9.

The common main lobe, formed in the manner discussed above, defines the combinations of frequency and time misalignments which jointly constitute tolerances acceptable to the filter. Comparing the diagonal ridge of the ambiguity function for f.m. with the single sharp peak of equal width, for pseudo-random "noise" modulations, it will be found that the tolerances in unfavourable circumstances (*i.e.* "across" the ridge-shaped ambiguity function) are much the same. However, in favourable cases, (*i.e.* for deviations along the axis of the ambiguity function), the f.m. system can be up to  $FT$  times better off. (Short pulses or long C.W. signals may also be regarded as having ridge-shaped ambiguity functions, parallel to the frequency and time co-ordinates respectively).

One likely cause of distortion is a varying range rate. Each part of the transmitted signal waveform is then compressed (or stretched) in accordance with the instantaneous range-rates, expressed as fractions of the speed of propagation. The pertinent range rates are those of:—the transmitting transducer (at the time of emission of the given portion of the wave-form), the receiving transducer (at the time of arrival of the relevant part of the echo), plus twice that of the target (at the time of reflection).

As illustrated by the dotted lines on Fig. 10, frequency modulation (more accurately cycle-time modulation) of the initial wave-form requires a time shift to make the initial and Doppler-compressed wave-forms match (for much of their length). Indeed this is the origin of the diagonal shape of the ambiguity function on the range/Doppler plane.

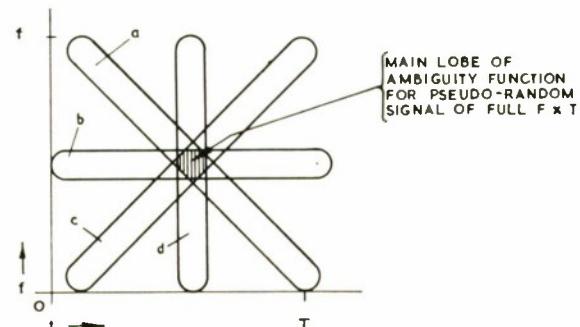


FIG. 9. Four intersecting ambiguity functions due to:—

- (a) "Upwards" f.m.
- (b) C.W. of duration  $T$ .
- (c) "Downwards" f.m.
- (d) Pulse of bandwidth  $F$ .

If the modulation produces a progressive increase of cycle duration with time, as in Fig. 10, then the aggregate range displacement during the echo, resulting from a sustained range rate, will contribute towards the time shift otherwise required to balance the Doppler shift. With a modulation law producing a linear increase (or decrease) of carrier cycle time, with time within the wave-form, the time shift required is constant over the full length of the received signal, and hence the design (or response) of a matched filter

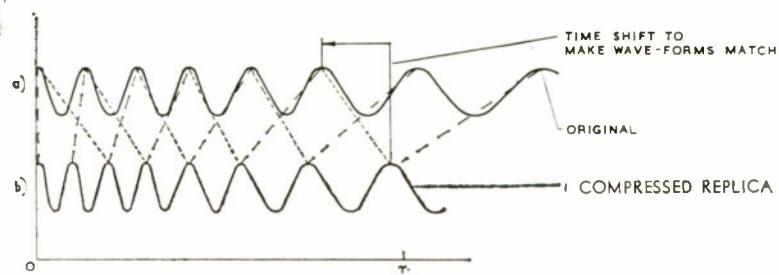


FIG. 10. Doppler compression of f.m. waveform:—

- (a) Transmitted wave form.
- (b) Compressed echo.
- Joins original to compressed replica
- - - Joins compressed wave to portion of original equal length.

is virtually independent of steady Doppler effects. See Fig. 11. This diagram shows how, under Doppler compression, the characteristic modulation line moves parallel to itself, on the time/cycle-duration plane, and each part of the wave-form moves on a straight-line locus joining it to the origin. Thus, by similar triangles (all angles equal), all parts of the wave-form and their relative timings are compressed by the same ratio.

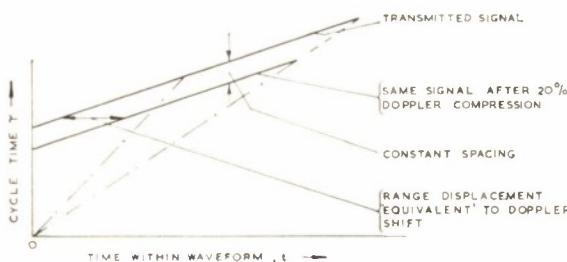


FIG. 11. "Doppler-invariant" frequency modulation. Linear cycle time modulation equals hyperbolic frequency modulation.

### Effects of Rapid Random Signal Perturbations on Matched-Filter Reception

In addition to progressive systematic departures from the basic signal pattern, we may be subject to rapid, random fluctuations. These may be—somewhat arbitrarily—considered from the point of view of amplitude, timing, frequency and phase distortions:

Unless there are large variations, with frequency or time, in the *amplitude* of the transmitted signal or in the received noise level (and hence in the relative gain of the elements of the matched filter), amplitude fluctuations by themselves are unlikely to have much effect on the coherent signal power emerging from the filter. They may however degrade the resulting signal/noise ratio.

Any steadily *progressive* changes of *timing*, due to a single, but varying, propagation path, can be catered for by the appropriate Doppler-matched-filter (whose tolerance to Doppler frequency shifts varies inversely with the total signal duration).

Since each constituent signal element (*i.e.* "quantum") lasts for one cycle at the "instantaneous bandwidth", the tolerable *random timing error* is proportional to this duration, and hence is inversely proportional to this "instantaneous bandwidth". If the modulation exploits the potentially available bandwidth in full, we are clearly concerned with the total bandwidth of the transmitted signal. Thus the system's tolerance to small random timing distortions, arising within the signal duration, is inversely proportional to the *bandwidth* of the signal.

The system's tolerance to rapid fluctuations of frequency, on the other hand, is clearly proportional to the "instantaneous bandwidth".

Excluding apparent or actual frequency fluctuations due to engineering imperfections, frequency variations are likely to be due to the Doppler effect associated with path-length variations. However, since the Doppler effect depends on the *rate* of change of path-length and any timing error depends on the *aggregate* change of path-length, the two aspects may normally be considered separately. Hence the probability density function of "instantaneous signal location" may be represented as an elliptical "splodge" on the time/Doppler plane (tilted only if the two parameters are correlated), and we must design the overall system to keep this as far as possible within the main lobe of the "ambiguity function" on that plane. The f.m. ambiguity function (*i.e.* a ridge of the same width as the single peak for pseudo-random noise of equal time-bandwidth limits) can offer a useful advantage in tolerance to such random perturbations along its major axis.

Any effects tending to influence the instantaneous *phase* within one frequency/time quantum are averaged vectorially, and appear as a mean change of phase and amplitude of the resulting signal element. The permissible tolerance to the *mean* phase over a signal element may be related to the preceding discussion on random *time* fluctuation, since the duration of one signal element represents one cycle of phase.

### "Optimum" Mix of Coherent and Non-Coherent Integration

Any pattern of instantaneous signal vectors  $A' \exp j\theta'$ , differing from the reference pattern  $A \exp j\theta$ , will modify the matched-filter output in the ratio  $(A' \exp j(\theta - \theta'))/A$ . The attempt at coherent integration, implied in the use of a matched filter, is then beneficial only over such intervals of time as satisfy, say,

$$-\pi/2 < (\theta - \theta') < +\pi/2.$$

Hence the ideal matched filter can be optimally adapted to the expected signal distortions, by splitting it into smaller constituent filters meeting this criterion, and then combining the outputs of these partial filters non-coherently. Thus if, say, accelerations produce a significant *change* in the Doppler shift, within the signal duration, one way of handling this problem would be to split the receiving system into  $p$  adjacent, smaller matched-filter arrays, each using a separate portion of the total received signal energy. For instance the output bus-bar of Fig. 1 might be divided into  $p$  consecutive sections, each handling  $1/p$  of the transmitted wave-form. This would allow only  $1/p$  of the time for a significant change to develop within the signal

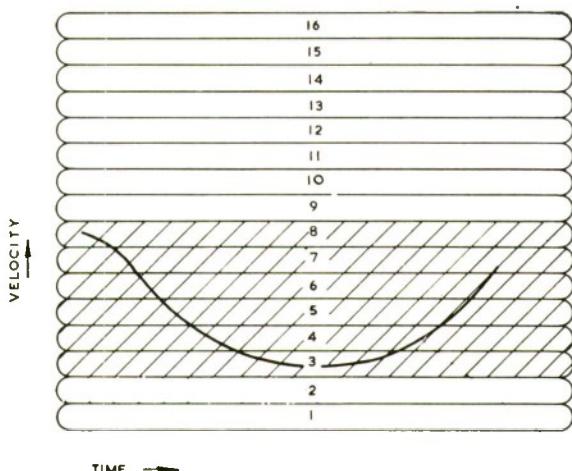


FIG. 12 (a) High velocity resolution.

in the reduced coherent matched filters. Those combinations of outputs corresponding to plausible and relevant changes of the Doppler shift, from one of the  $p$  partial filters to the next, could then be combined non-coherently. Ideally the frequency and time resolution of the partial filters should bear a common ratio to the Doppler frequency (*i.e.* velocity) and time spread of likely target signals. See Fig. 12.

If the received signal retains its internal coherence over less than one cycle of its ideal "instantaneous bandwidth" (corresponding to that of the transmitted signal), the filter bandwidth would clearly have to be widened appropriately. The subsequent non-coherent signal integration, in accordance with the above principle, would then merely result in the determination of total power (or possibly in weighted power addition).

If thus  $p$  equal, previously coherent portions of the received signal must now be combined non-coherently, and if these  $p$  partial signals have similar, fairly low ratios of signal to (non-coherent) noise, the loss of coherence will degrade the resultant signal/noise ratio by

$$1/\sqrt{p'} \text{ where } p' \gtrsim p$$

However, in general the full  $p$ -fold coherent integration would also imply the selective reception of signals arising from one of  $p$  regions of the range/Doppler plane. Hence the reduced degree of coherent integration will:

- (i) avoid the need to "look" separately for signals from these  $p$  regions,
- (ii) lose the opportunity to classify signal sources according to these  $p$  regions of origin.
- (iii) lose the opportunity of discriminating against noise or interference not coinciding with the wanted signal in these  $p$  regions.

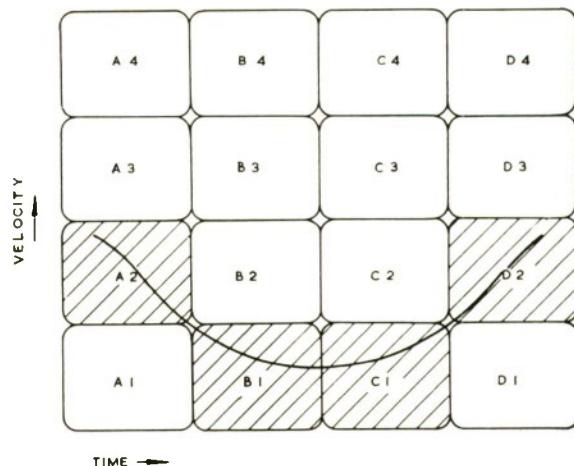


FIG. 12 (b) Reduced velocity resolution.

For Fig. 12 (a)	3 4 5 6 7 8
For Fig. 12 (b)	A2 B1 C1 D2

FIG. 12 (c). Non-coherent filter combinations to cover given velocity pattern.

FIG. 12. Partial matched filters with ambiguity functions of different "Aspect Ratios" combined non-coherently. (Note. Actual range and velocity pattern shown by curves in (a) and (b). The smaller shaded area in (b) implies less noise and better pattern selectivity.)

The main objects of partially non-coherent integration in the time dimension (apart from economy) are likely to be:

- (i) to accommodate multi-path arrivals,
- (ii) to allow less time (within each coherently integrated section) for significant changes in the transmission path to take place, and
- (iii) to increase the frequency tolerance.

With linear f.m., the use of  $p$  partial filters, each accepting  $1/p$  of the frequency sweep, reduces by  $1/p$  both the time and frequency spans of the signal to be integrated coherently. This results in an ambiguity function which is still a diagonal strip of unit area on the time/Doppler plane, but its length is reduced and its width is increased  $p$ -fold, and thus its tolerance to random or unfavourable changes in *both* dimensions is improved by the same factor. This contrasts with random modulation, where a partial signal of  $p$  times shorter duration still contains the full spectrum—and hence retains its full sensitivity to timing; however the  $p$  times shorter observation time does give a  $p$  times coarser frequency discrimination—and hence wider frequency tolerance.

## Tolerances in Direction of Arrival and Further Generalizations

The discussion so far has been concerned with collecting the signal energy despite changes of its position in the time and Doppler dimensions. Similar problems can arise in the angular dimensions of azimuth and/or elevation. In this case it is the size of the transducer array, in wave-lengths, which determines the fineness of its angular discrimination.

If the beam moves by less than its own width, the danger of a receiver or reflector drifting out of the beam, within the signal duration, decreases with increasing range—where full sensitivity normally matters most. The propagation path can be broken by rotation of the transmitting or receiving transducer (or a reflector), or by relative lateral translation. In addition, the path might be bent by time-dependent refraction effects.

Once again, these possibilities—if significant—can be taken into account by appropriate electronic steering of the beam for each likely and relevant pattern of angular changes, or by restricting coherent detection to p consecutive portions of the signal, and then non-coherently combining plausible sequences of these partial signals, associated with adjacent beam positions.

The spatial phase coherence over a transducer array can be effected by inhomogeneities in the propagating medium or irregularities in any reflecting surface, provided these disturbances are *in the near field*: any irregularities within the main lobe, in the far field, are, by definition of that lobe, irresolvable. Their relative amplitude and phase will jointly determine the amplitude and phase of the received signal, but they cannot significantly affect the distribution of that amplitude and phase over the receiving aperture. (With “super-gain”, the main lobe is narrowed, the aperture distribution becomes irregular, and the spatial limits of the “near field” are extended. However, subject to these provisos, the above statement still applies, even though the aperture distribution itself is neither smooth nor uniform.)

Where near-field inhomogeneities are limiting the size of aperture over which coherent integration is possible, we are faced—once again—with only part of the signal (now limited in *array space*, in two or three dimensions) being integrated coherently, and the outputs of several such integrators being combined non-coherently. Since this widens the beam, it also provides an alternative means of coping with unexpected rotations or translations of the propagation path. The total requirement for non-coherent array processing—if any—arises then from the statistical combination of the effects of these inhomogeneities and of the

movements of the propagation path discussed above.

Similar limitations to the coherent array aperture arise also in scatter communications, where either:

- (i) the volume of medium common to the transmitting and receiving beams must be kept large enough to give an acceptable probability of containing a suitable scatterer, or
- (ii) the volume contains a large number of such scatterers, and any increase in (coherent) receiving aperture gives a proportionate increase in collection efficiency of the energy *from a proportionately reduced proportion of the transmitting beam*. If the scatterers can be regarded as coherent, there is then no net gain from the increased aperture. This could be thought of as an extended effective source of radiation which can maintain coherent illumination—arising from the full source—over only a limited receiving aperture.)

If the receiving aerial sensitivity is inadequate, signals from several parallel receiving aerials will then have to be combined non-coherently, in the same manner as in “space-diversity reception”. These may be small-aperture aerials each encompassing the whole of the scattering region within their beam-width, or large-aperture ones, each covering a separate proportion of the scatter region.

A suitably weighted additive combination is clearly the optimum processing of such parallel signal channels when the signal-to-noise ratio in all of them is low. At higher signal levels, various logical processes to minimize interference, distortion or fading may be more appropriate. These conclusions apply of course to diversity reception in the time and frequency dimensions as well as to spatial diversity.

In a medium of variable dispersive characteristics, the relative phase of different spectral regions of the received signal may not be maintained adequately for coherent integration over the full spectrum. In this case (as an alternative to the provision of a range of alternative phase changers), the spectrum may be broken up into a number of partial spectra, each with its own partial coherent matched filter. The outputs of these filters would of course be combined non-coherently.

The most likely change in the frequency dimension is however the Doppler effect, *i.e.* a compression or expansion of the time scale of the complete received wave-form without alteration in its intrinsic wave shape (or its signal energy). This need then not preclude coherent integration in an appropriate filter, matched to the given Doppler range-rate.

In pulse-to-pulse integration, a changing effective path-length, in addition to producing Doppler frequency shifts, can in some cases make it quite difficult to keep the signal within a range-gate or time-slot for the appropriate observation time. A filter matched to a high Doppler velocity may then have to be designed to be also associated with an appropriately moving time (range) slot. However, once again the time for a change to become significant can be decreased by the use of  $p$  consecutive partial matched filters. The outputs of appropriate sequences of range/Doppler filters, each sequence representing plausible and relevant target manoeuvre (or other physical situation), can then be combined non-coherently. See, for instance, Fig. 12b.

Quite generally, the received signal, to be integrated coherently for matched-filter reception, is distributed over the two dimensions of the frequency-time plane and the two geometrical dimensions (or three, including end-fire array elements) of the receiving aperture. If a departure from the expected pattern of relative amplitudes and phases exists—or develops—in any one (or any combination) of these five co-ordinates, this can impair or destroy the internal coherence of the received signal. The liability to all these coherence losses must therefore be assessed, prior to the design of a specific system.

### **Conclusions**

It is shown that, in a band-spread signalling system, it may not be permissible to choose the bandwidth solely according to the timing accuracy

desired—or the circuit bandwidth available. Neither may the duration of the spread signal be determined solely by the desired frequency accuracy or by the ratio of desired energy to available mean power. Nor indeed may the receiving array configuration be wholly defined by the desired angular gain—or the aperture available.

If the elements of received signal energy, distributed in frequency and time and over the two (or even three) dimensions of the receiving array, are to be integrated coherently, changes affecting the coherence of the signal within these dimensions must be avoided. This paper indicates in general terms an approach to:

- (i) assessing the tolerances arising from this consideration,
- (ii) assessing the magnitude of the possible coherence loss,
- (iii) the choice of modulation law and other system characteristics to take account of these tolerances,
- (iv) the optimum combination of coherent, non-coherent and logical processing to match given systems constraints,
- (v) (incidentally) the selection of a modulation law to produce an ambiguity function, meeting given special requirements.

### **Acknowledgement**

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# ELECTRONIC EQUIPMENT DESIGN FOR EXTREME CLIMATIC CONDITIONS

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## SUMMARY

This paper is concerned with the engineering (as opposed to system techniques) design problems of electronics and ancillary equipment, experience being drawn from aircraft and ground military radars, and S.A.G.W. systems. The paper outlines the basic problems, attempts to define "extreme" conditions, touches upon historical experience, indicates how the basic problems influence design, surveys contemporary approaches for alleviating the environment and suggests a possible wholesale solution to many of the problems by the application of microelectronic techniques.

## Introduction

The problem of designing and achieving an acceptable standard of reliability in military equipment for normal deployment becomes even more intractable when trying to meet "extreme" climatic conditions associated with military activities. The task for normal applications is made more difficult by lack of systematic feedback of field defect data and analysis. In the case of climatic extremes, there has been virtually no field experience which, over the years, might have fed back defect problems for analysis in the laboratory. Except for performance, the primary problem of design is defining in engineering terms the environmental conditions embraced by the statement "extreme conditions". If we examine SDM(L) 89/3,<sup>(1)</sup> the basic U.K. military requirement for temperature and humidity, for definitions and exclude the "normal" case, only "Severe Cold" at -68°C remains.

The definition of extreme conditions needs translating into quantitative terms against the subjective limitations of man attempting to wage war, suspended or active, in environments sufficiently hostile to impair his own performance. Tropical jungle, arid desert, arctic winter, mountain altitudes, high flight altitudes, are not just images of human endurance which spring to mind, but difficult design problems for electronic equipment.

problems made more difficult and costly by the lack of quantitative data for such environments. An attempt has been made in Appendix 1 to arrive at some natural severity levels for extremes in order to contrast these with the equipment limitations, but it is hoped that other papers in the Symposium \* will give a much clearer picture than hitherto on this subject, particularly on rational "extremes" for man. Because all the equipment problems stem directly from the environment, this subject is dealt with in some detail.

The remaining problems fall under the loose headings of performance (and reliability) ergonomics, i.e., ease of use, weight, bulk, maintainability, and power supplies. No clear priority can be attached to any of these requirements; they interact, and their ultimate solution will be a compromise in which reliability is sacrificed for cost, performance for weight, cost for power supplies, and so on. This paper does not discuss performance or the problem of logistics which, in terms of transport and supply, may itself set the limit on an equipment otherwise capable of being successfully operated under extreme conditions.

## Problems of the Environment

Table 1 shows the natural environments with which we are concerned and summarizes their design significance. None of these environments exists singly in terms of equipment design and there will always be at least three, usually five, acting together. Their influence on equipment is discussed later, but it is useful to say now that

\* This paper was first presented at the Commonwealth Defence Science Organisation Symposium on "Problems of Warfare in Extreme Conditions," Ottawa, Canada, 1966.

their adverse effects result either in equipment performance or reliability defects which are theoretically amenable to correction by design, or as system propagation limitations for which the designer has no corrective solutions. Generally, it is not the environment which creates the problem but the magnitude, better expressed as severity, of that environment.

The range of environments is not reduced by excluding those which impair propagation performance because a clear sky for propagation could exist with the equipment recovering from a sand-storm, covered with hail or dripping with rain. Moreover, the concern with "extremes" implies unpleasant deployment areas and the non-existence of protective buildings for the equipment. Normally, an equipment is designed to survive undamaged all the natural environments up to the worst severity levels, but the physical limitations of man and equipment (coupled with economic factors) set less stringent limits on the severity levels under which functional performance is required.

Table I shows that if we ignore propagation problems the natural environments can be translated into three specific design approaches. Environments a, b, c become largely a heat balance problem in which no part or assembly function is allowed to exceed its temperature rating. Environments e to l become moisture exclusion matters to be taken with environments m, n, o, all of which can be designed out by appropriate sealing techniques; if these environments are not isolated they must be endured and here serious problems arise. Environment p, corrosion, can be taken with d and q which all have to be designed for endurance in full. The two environments r and s are largely propagation problems. The original range of environments can now be reduced to three classes of design activity—heat, isolation and endurance.

In association with the natural conditions must be considered the basic environment—elapsed time; this causes all materials to change and decay from first manufacture, the process being accelerated by all natural global environments other than below-zero temperatures. The rate of acceleration is largely dependent upon the severity level of the temperature, moisture and sunlight environments, but the full mechanics of the processes are not well understood. It follows that elapsed time is closely identified with reliability, but unfortunately little of the quantitative information on environmental severity is associated with the period of time over which a given severity level existed.

Meteorological organizations provide the major source of basic data on natural environments, but their established system of recording such quanti-

ties as temperature, humidity, solar radiation, rainfall, etc., mostly uses "Stevenson screen" conditions, which are not easily translated into engineering design parameters. For particular equipment problems, as in aircraft or G.W.s *in situ* measurements may be made; but since they will be specific to the equipment, because of the interaction of that particular equipment with the otherwise natural environment, they will have little relevance for other equipments. Moreover, the equipment will, by this time, be far advanced in design, whereas the information is most needed at the earliest stage in development. In an attempt to improve the situation on generalized data, attempts have been made, originally on behalf of the Army, to introduce generalized references by measuring

TABLE I. Natural Environments in Relation to the Design of Military Electronic Equipment.

National Environments	For a functional equipment the environment may:			May Also Affect Propagation
	Be Designed Out	Be Alleviated	Not Be Relieved	
(a) Solar Radiation			✓	
(b) Temperature High			✓	
(c) Temperature Low		✓		
(d) Ice				✓ on aerials
(e) Humidity Local	✓			
(f) Fog	✓			✓
(g) Clouds	✓			✓
(h) Free Water Rain		✓		✓
(i) Condensation	✓			
(j) Sea	✓			On venti- (✓)
(k) Rivers	✓			lated equipt. (✓)
(l) Melting Ice	✓			on aerials ✓
(m) Dust and Sand	✓			
(n) Atmospheric Pressure		✓		
(o) Biological		✓		
(p) Maritime Corrosion				✓
(q) Wind				✓
(r) Snow and Hail			✓	✓
(s) Thunder and Electrical Storms				✓ ✓

The table indicates the influence of the environment on the design approach for "normal" severities, the final column relating to the quite separate problem of propagation limitations. Excepting r and s all the above environments must be taken into account in the functional design of an equipment to ensure that its performance and reliability are not impaired within the severity limits given or implied in the Military Requirement. An equipment not in use must be protected to survive undamaged the raw environment whether given a temporary package or self-protection.

TABLE 2. Severity Levels for Extreme Climatic Conditions.

Environment	Average Man* Suitably Clothed	Equipment (Man protected by vehicle?)	
		Operating	Survival
High temperature	50°C at 30% RH 4 hrs.	+150°C (in aircraft)	+90°C
	64°C at 10% RH 1 hr.	+ 58°C (all other)	+70°C
	39°C at 90% RH 1 hr.	+ 40°C (reliability)	+70°C
Low temperature	-34°C (5 knots) Indefinite	- 55°C (in aircraft)	-70°C
	-72°C (5 knots) 1 hr.	- 40°C (all other)	-69°C
Solar heating	Common at 200 CHU's/ft. <sup>2</sup> /hr. for 5 hrs.		
High humidity	90% at 39°C 1 hr.	100% at 35°C also 32 in.	
	100% at 33°C 4 hrs.	S.W.G. Vapour pressure	
Low humidity	?	5% at 70°C also <5% at -60°C	
Wind (plus gusts)	50 (70) knots	50 (70 knots) 70 (100) knots	
Rain (intensity)	100 mm in 10 mins.	200 mm in 1 hr. 1000 mm in 24 hrs.	
Snow	?	— 0·2" d. stones Survival limits determined by test	40 lb./ft. <sup>2</sup>
Hail			20" d. stones
Ice			
Dust and sand	0·01 mg/ft. <sup>3</sup>	0·5 mg/ft. <sup>3</sup> 30 knots	40 mg/ft. <sup>3</sup>
Corrosion	—	Can only be covered by standard test conditions	
Biological	—		
Altitude/pressure	10,000 ft.	Aircraft equipment and missiles up to 70,000 ft. All other up to 8,000 ft.	

\*It is impossible to reduce man's limits to simple statements because of the effect of exposure period, work conditions, wind effects, acclimatisation, etc., etc. The sources of data on man for temperature and humidity are Refs. 2, 11, 12, the remaining material is derived from Refs. 1, 6, 10. Survival for dust, Ref. 13.

N.B.—This information has no authority, it suggests levels for discussion only.

temperature and humidity under field reference conditions. Here the severity of the environment is categorized either by "Shelter Storage" or "Open Exposure". In the former the measurements relate to equipment and stores held under conditions of partial protection from the weather by means such as unconditioned buildings, Nissen huts, tarpaulin covers, stationary vehicles and the like. Open-exposure is self-evident and the equipment sees the raw environment. In the shelter-storage case an equipment would not normally be operating, though this may not necessarily apply to a vehicle-contained equipment; for open-exposure the equipment may be idle or active.

### Summary of Extreme Conditions

In trying to rationalize those conditions which might be defined extreme and to attempt some assessment of severity levels, it seems necessary to consider whether man will be protected by the environment of his vehicle or not, and if so what will be the operational and survival severity levels for all three categories. Table 2 suggests the severity levels assessed from Appendix 1 for extreme conditions.

### Ergonomic Problems

"Ergonomic" is used to embrace the four factors of weight, bulk (*i.e.* physical size), ease of

use and ease of repair. The broad definition of the word seems to be the matching of human capabilities to the man/machine environment such that optimum utilization of man and machine is realized.

#### *Weight and Bulk*

These design problems are not unique to the fields of aircraft and missile equipment, although virtually all the experience is held by the makers of airborne equipments. Next to the environment, weight and bulk exert most influence on operations under extreme conditions because they scale directly from all the detail problems. Increasing weight and bulk adversely influences the manning needed for maintenance, transportation and storage, air-lift potential, logistics, handling, abuse, conspicuousness in deployment (both visual and aural), mobility, power supplies, fuel burdens and costs.

Weight and bulk are primarily influenced by complexity which stems directly from the engineered solution to the military technical requirement which dictate the functional performance, deployment and transportation conditions. If the solution employs a high proportion of electronic components and processes, then electric power is used at very low efficiency. It is not suggested that any significant improvement in the operating efficiency of contemporary electronics is possible (except by the application of micro-electronics) but it is simply a fact that an electronic function operating at only a few per cent efficiency automatically results in relatively high weight and bulk penalties.

#### *Ease of Use (2)*

Matching the capabilities of man to the equipment most closely accords with the classic definition of ergonomics; this requires the man to be comfortably integrated with his machine at the correct height, optimum posture, scientifically distributed body load on feet, eyes conveniently aligned with the work, all in an ideal conditioned climatic environment. Man under 'Extremes' seems likely to have little analogy with the maximized comfort of human engineering in the factory!

It is self-evident that matching man to an equipment can only be dealt with on the merits of the equipment concerned and it is not proposed to attempt discussion in this paper. There are however, a few guides lines worth reiterating for the extremes:

#### *Controls*

Position so that selection can be made unambiguously in poor light with the minimum of

mental and physical effort. In a complex operation involving all limbs see that no one limb is overburdened.

#### *Information Presentation*

In both the visual and aural cases, scientific consideration is needed to reduce the work load in these senses and to present information with the minimum tendency to error.

#### *Control Knobs*

Identification by feel and manipulation with sticky fingers or arctic gloves must be possible.

#### *Control Movement*

Direction of movement should be related to the response affected by the control. The kind of resistance afforded by the control should be matched to the need for "feel" or purpose or avoidance of accidental operation.

#### *Weight*

Not more than 60 lbs. wt. per man.

#### *Identification*

Label purpose with common words. Use no colours liable to change by sunlight (colour banding of cables with plastic idents is a liability here).

#### *Dynamics*

When matching human response to machine dynamics evaluate the integrated performance under the most adverse climatic and mechanical environment for the human.

#### *Moisture*

Can the equipment be used (as opposed to its being functionally unreliable) with a film of condensate all over it? Are dials and scopes obscured, are controls affected, are there lethal tendencies?

#### *Ease of Maintenance*

Maintainability describes the ease and speed with which an equipment defect may be diagnosed and repaired. A poor reliability may be acceptable if the defect can be found and corrected with low cost penalties in time and money. The real problem is that of speed, ease and accuracy in locating a defect. Diagnostic equipment, even if available under extreme conditions of deployment, is built from the same components, materials and processes that go into the equipment being diagnosed, and test equipment is usually a Cinderella activity alongside the main project. Consequently it is highly probable that the test equipment will not only be conceived to an inferior design standard, but it may well be more unreliable than the equipment it tests.

It cannot be over emphasized that maintainability must form part of the embryonic design if costly re-design is to be avoided, for once the development hardware begins to be frozen it is usually impossible to introduce retrospective maintainability attributes. One important feature of this early work is to decide upon a maintenance policy, especially in terms of manning, for in maintenance terms the least skilled are usually the actual operators but under extreme conditions presumably one envisages personnel as self-dependent as possible and not a separate team of skilled non-operators for maintenance. Under extremes one may assume that diagnosis and repair are affected in very difficult conditions. The lighting may range from unbearable sunlight to a defective flashlamp; accommodation in which to lay-out diagrams may be restricted, and even the simplest test equipment or tools can require great mental and physical effort when working in uncomfortable conditions; from mud to blowing sand, from fingers slippery with perspiration or so frozen that only coarse non-discriminating movements can be made. Add high psychological stress, add illness, add crawling insects, etc., etc.

In a paper such as this it is impossible to enter into practical detail such as limiting weights, positions of C. of G., fasteners, connector and cable design, test monitoring facilities, shapes, size of access screws, safety features. The disturbing feature is that there appears to be abundant literature (Ref. 2 is typical) and knowledge in detail on the subject, but the solution to the right policy for ensuring the provision of adequate and reliable diagnostic test equipment has remained intractable for over two decades. The case for built-in test facilities of the digital or go-no-go philosophy and/or for economic throw-away module construction seems to be unanswerable for extreme conditions. It does seem, however, that a near-revolution in functional circuit engineering solutions to problems is necessary before built-in or self-checking diagnosis is a practical proposition.

### Power Supplies

Deployment under extremes means complete dependence upon self-carried supplies such as P/E generator sets, active, dry or thermal batteries. It is unfortunate that accuracy, if not reliability, in almost any radar system is dependent on power supplies closely regulated in frequency, in voltage, and in clean waveforms. These parameters are difficult enough to maintain under normal conditions for valved-type equipment, but transistorized equipments carry an additional problem of switching transients in which destruction of many types of transistor is immediate in the presence of a transient of the right voltage.

The conventional type of P/E set has a reputation for unreliability, poor starting characteristics under low temperature, diminished power in elevated terrain, indifferent voltage regulation and high noise level. The argument that level positioning and correct maintenance of the engine side would avoid much of the unreliability is undoubtedly true, but would seem to be clearly irrelevant for extreme conditions and there is need for some development work in this area. Secondary cells offer little prospect for improvement in the specific output, i.e., the power to weight ratio, and current development offers only fringe benefits in temperature range, storage life and improved charging methods.

The potentialities of new sources such as thermo-electric systems or fuel cells offer significant weight saving with little apparent worsening of electrical characteristics. U.K. developments on fuel cells concern capacities up to 500 watts with features such as quiet operation, low infrared radiation, high efficiency and low maintenance. The need to use exotic fuels e.g., methanol, hydrazine, and a restricted temperature range of 10°C to 60°C may hold objections. Thermo-electric generators offer silent operation, high environmental capabilities and almost indefinite life but research is slow and concerns devices offering capabilities up to possibly 500 watts.

### Defect Tendencies

The liability of an environment to create those defects leading to unreliability depends upon the merits of the equipment, but to give some perspective to the overall problem it is best generalised into three types of defect as indicated in Table 3. They are assigned priority a, b and c, dependent upon which type presents the highest liability. Type 1 is immediate and catastrophic; Type 2, termed drift, occurs over a relatively short period, maybe minutes or hours, during which functional parameters drift outside the tolerance permissible to

TABLE 3.

	Immediate (1)	Delayed (2)	Long-Term (3)
Temperature High	a	a	a
Temperature Low	b	a	-
Solar Radiation	c	b	a
Humidity	c	b	a
Rain	c	a	b
Snow, Hail, Ice	-	a	-
Wind	b	a	-
Dust and Sand	b	a	-
Maritime Corrosion	-	-	a
Biological	-	-	-
Altitude Pressure	b	a	-

maintain satisfactory performance; Type 3 covers long term deterioration in which time, as opposed to its stabilizing influence in Type 2, exerts a natural decay mechanism contributing towards a defect tendency also accelerated by the environment. The priorities suggested hold irrespective of extreme or innocuous conditions. Propagation defects are ignored because fundamental performance limitations cannot rightly be classified as unreliability.

In practice the causes of unreliability are roughly shared between random failures and design weaknesses, ignoring the contribution due to human fallibility. A random failure is one in which it is impossible to diagnose the cause or one in which it is due to a non-systematic cause; a design weakness is one in which the failure can be demonstrated to be due to specific causes. The following discussions concern only the tendencies towards design weaknesses since the liability to random failure increases with all environmental severities, except possibly low temperature.

#### Temperature

High temperature is one of the principal causes of unreliability in electronic and associated equipment. The need to seal and to minimize the physical size of much electronic equipment aggravates the problem of cooling, especially where airborne equipment is concerned, because of the tendency to operate equipments at high thermal loadings.

Some common effects of extreme high temperatures are:

- Catastrophic failure and fire risk
- Seized mechanisms due to differential expansion of dissimilar materials
- Ditto, due to excessive temperature gradients in similar materials
- Loss of lubricant or fluids through seals due to reduced viscosity
- Circuit malfunction, frequency drift, instability due to changes in electronic component parameters.

Some common effects of extreme low temperatures are:

- Seized mechanisms due to b or c above or due to the use of inadequate low temperature lubricants or moisture contaminated lubricants
- Leakage of seals (especially rubber based seals) retaining lubricants, hydraulic fluids and the like
- Leakage of air seals, especially the protective seals of electrical connectors and sealed equipment
- Failure of cables due to flexing
- All icing problems when moisture is present
- Circuit malfunction as (e) above

- Great difficulty in manipulating controls through protective clothing.

Table 4 is a valuable pointer to the present-day vulnerability of typical materials. Fig. 1 suggests a qualitative curve for reliability against temperature plotted on the basis of defect experience both in the laboratory and in the field. It indicates that the optimum "ambient air" temperature limits for contemporary military electronic equipment range from approximately  $-40^{\circ}\text{C}$  to  $+50^{\circ}\text{C}$  if any acceptable level of reliability is to be expected.

#### Solar Radiation

Solar radiation manifests itself either as heating or as an actinic degradation, either acting alone or aggravated by the presence of moisture or oxygen. The materials most subject to chemical degradation from sunlight are the organic compounds belonging to the polymer class such as plastics, rubbers, textiles and surface coatings, and normally the ultra-violet wavelength is most damaging. The heating content of solar radiation is taken into account in the temperature environment and needs no further comment. It is of interest, however, to note<sup>(3)</sup> that extreme temperatures of surfaces (e.g. an aircraft wing, a metal box) exposed to the sun even in the U.K., can attain  $+70^{\circ}\text{C}$ , and nearer the equatorial latitudes extreme values for similar objects can range from 80 to  $100^{\circ}\text{C}$ .

Plastics may be conveniently divided into thermoplastics which are softened by heat and thermosets which are permanently hardened by heat. The deleterious effect of sunlight generally produces a photo-chemical reaction manifest either as loss of strength, embrittlement, crazing, cracking,

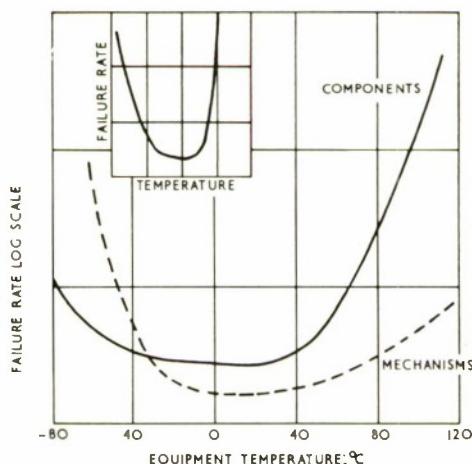


FIG. 1. General pattern of temperature failure of electronic equipment (inset—idealized presentation per component).

TABLE 4. Vulnerable Temperatures

Item	Low <sup>2</sup> Limit °C	Defect Tendency <sup>1</sup>	Upper Limit °C	Defect Tendency <sup>1</sup>	Notes	
<b>Metals</b>						
Light alloys of Aluminium and Magnesium	(<)-70	Satisfactory	+150	Reduction in tensile strength		
Copper	(<)-70	Satisfactory	+250	Rapid Oxidation and loss in tensile strength	Usually nickel plated for operation at elevated temperatures	
Carbon steels	-30	Low Izod values preclude high stressing	+several hundred	Oxidation and loss in tensile strength		
Titanium alloys	-70	Deterioration of impact strength	+400/500	Reduction in tensile strength	High temperature performance depends on alloy	
<b>Plastics<sup>3</sup></b>						
P.V.C.	-30	Hardening	+70	Softening and loss of plasticiser		
Polythene	-25	Embrittlement, cracks on bending	+80/105	Softening	Depends on grade	
Polyamides (Nylons)	-30	Low impact strength	+100/150	Softening	Depends on grade	
Polycarbonate	-60	Embrittlement	+125	Softening		
PTFE	(<)-70	Satisfactory	+250	Charring		
<b>Elastomers<sup>3</sup></b>						
Natural rubber	-40	Hardening	+70	Softening	Performance of synthetic rubbers varies widely according to elastomer mix	
Synthetic rubbers	-25/-60		+70/+130	and chemical deterioration		
Silicone rubbers	-65		+150			
<b>Electronics</b>						
Typical passive components	-40/-50	Material degradation	+100/125	Material degradation	Dielectric and plastic constituents degrade at temperature extremes	
Transistors	-20/-55	Performance degradation	+60/+150	Burn-out		
Silicon integrated circuits	-55	Performance degradation	+150	Material degradation		
Oils and hydraulic type fluids	-60	Increasing viscosity. Solidification of constituents (waxing)	+150	Decreasing viscosity and lubricating	Fire hazard increases with temperature for many fluids	
Chemical explosives	-40	Physical change	+60	Oxidation		
Ceramics	(<)-70	Satisfactory	(>)+500	Chemical deterioration and sensitivity hazard	Most ceramics brittle at all normal working temperatures	
Batteries	-40	Deterioration of electrical performance	+60	Desiccation		
Gyros	+10	Performance degradation	+50	Chemical deterioration voltage increase		
Servo type control motors	-25	Performance degradation	+70	Performance degradation		
Man	-25	Frostbite	+60	Desiccation		

1. The significant phase of the effect, which may already be active, due to increasing the temperature beyond the limit given. The effect is deemed to be solely due to temperature and divorced from other possible causes such as humidity, solar radiation, oil contamination, etc.

2. Vulnerability to temperatures below -70°C not considered.

3. Some plastics and many elastomers are vulnerable to ultra-violet radiation. Many elastomers are also adversely affected by oils, hydraulic fluids and solvents. The properties of plastics may be modified by irradiation at manufacture.

discolouration, or loss of electrical characteristics. Much of this tendency can be reduced or delayed by including an ultra-violet absorber in the plastic mix but thin sheets and coatings still tend to have their properties more seriously impaired.

Natural unvulcanized rubber oxidizes and perishes rapidly, and even vulcanized rubber is relatively prone to "light-cracking" after extended periods of sunlight. Natural rubbers offer good low temperature behaviour but poor high temperature performance and poor resistance to most fluids. There has been considerable development in the field of synthetic rubbers to combat the three problems of sunlight, high temperature and fluid resistance, but synthetics are not chemical equivalents of natural rubbers. The synthetics give better resistance to swelling in oils and decomposition by heat or sunlight, but in the photo-oxidation of enoprene, S.B.R. and nitrile rubbers the dominant tendency is towards "light-cracking" with loss of extensibility and increase in hardness, both of which affect sealing characteristics, though usually the tensile strength is unaffected.

In the evaluation of the photo-chemical reaction of materials to sunlight there are great gaps in our knowledge largely because so few of the results are quantified either in terms of the extent and characteristics of the activation energy applied, or the measured change in properties of the material exposed. The reasons for these appear to be the great difficulty in simulating the sun's spectrum and spectral energy distribution, discouraging serious study of the problems.

#### *Humidity and Free Water*

It is a fine point whether solar radiation or moisture causes the most widespread and long term damage to materials and equipment. The problems are similar in that the process of deterioration is slow and rarely evident until the damage is done. Progress, in the case of moisture, has become tangible only by sealing the equipment sufficiently well to prevent its ingress. It cannot be sufficiently emphasised that the process of deterioration is insidious and will defeat, if only through temporary neglect, the most carefully designed measures adopted to isolate the equipment from moisture.

It is strongly believed that primary deterioration is most rapid, for a given temperature, when the moisture content is virtually at saturation but short of precipitation, the reason being the high conducting paths afforded by moist air coupled with an oxygen content richer than would be the case with free water. The system of electro-chemical cells thus available promotes an environment which encourages electrical deterioration in components, dielectrics and insulators, and corrosion development, the main indications of the effect: the higher

the temperature at which high humidities exist, the more active the deterioration environment. Secondary deterioration arises through the medium of mould growth for which a staple humidity in a fairly narrow temperature band around 30°C is necessary.

An additional defect mechanism is that due to the pressure effect of high vapour pressures; a high vapour pressure will always seek towards equilibrium with a lower vapour pressure. This is the mechanism which promotes "breathing" and the development of free water inside nominally sealed containers and explains why so many apparently sealed (but in fact, inadequately sealed) equipments fail in the field. A further effect of the breathing mechanism is that containers such as an ill-ventilated aircraft or equipment will collect free water and when exposed to the sun subject their contents to saturation humidities at temperatures of 40°C or higher.

Tabulated below are effects typical of humidity or free water; the examples are not exhaustive and in the problem of isolating moisture, it is worth emphasising that the U.K. represents a problem little different from the wet tropics!

- (a) Deterioration of thermal and electrical materials indicated by slow, or fast, progressive loss of insulation or dielectric properties and in some cases by loss of structural length.
- (b) As (a) but caused by mould growth either as direct biological attack or via moisture held in suspension by harmless moulds.
- (c) Electrical malfunction due to change in dielectric properties or surface leakage paths of low resistance.
- (d) Condensed moisture bridging adjacent circuits.
- (e) Icing troubles.
- (f) Electrolytic corrosion of metals, especially where dissimilar materials exist at junctions. Outwardly this may be no more than a deterioration of appearance sufficient to undermine confidence in the user. Inwardly it progresses to tarnish contacts leading to plug and socket and wiping-contact failures. In extreme cases, corrosion will progress so far as to cause structural failure.
- (g) Rotting of organic materials.
- (h) Misting or fogging of optical devices. Inadequate sealing can result in fungi attack on lenses.
- (i) Pollution of static fluids if adequate ventilation, sealing or desiccation is not provided.
- (j) Rain erosion of aircraft skin materials especially leading edges, such as radomes or deicing mats, due to the high velocity impact of water.

- (k) There is no evidence to suggest that very low humidities promote adverse effects except in man, and in excessive brushwear in aircraft electrical machines.

#### *Ice*

The defect tendencies of ice are self-evident, notably that any build-up of ice on the moving parts of an equipment will result in impaired performance. While this effect can to some extent be designed out by the application of heat, one should consider whether or not the equipment as a whole can perform at all due to the adverse effects of even thin ice on certain transmitting and receiving components and on the aerial characteristics.

#### *Wind*

The defect tendencies of wind are those which directly affect navigation (here the functional limit is largely set by the vehicle and not its equipment) and those of wind force which are matters of endurance. The solution in the latter case is largely economic since theoretically there are no natural extremes against which equipment could not be designed, whether for function or survival; normally it would only be the aerial sections of equipments which would be concerned.

#### *Dust and Sand*

Apart from the obvious liabilities such as clogged up mechanisms, dirty bearings, and choked air filters, there will be the visible evidence of obscured optical devices and general cessation of all activity until an extreme dust storm has died down. Two less obvious defect tendencies are that high voltage areas in equipment, especially where high temperatures also exist, act as an electrostatic magnet for the very fine dust and lead to early malfunction, and that individual particles of dust, microscopic in size, will impair the behaviour of fine mechanism such as relays and gyros.

#### *Maritime Corrosion, and Biological*

This has already been dealt with sufficiently under moisture defects above.

#### *Altitude/Pressure*

The decrease in atmospheric pressure with increase in altitude results in three defect tendencies. In aircraft equipment, air cooling effectiveness rapidly diminishes though this problem does not really arise with surface equipment in mountainous regions because the decrease in ambient air temperature compensates. Second, in any equipment operating with high voltages, say several hundred volts upwards, the tendency to flashover increased markedly above about 10,000 feet so that either spacing distances have to be increased, which makes for penalties in size, or the

high-voltage area of the equipment must be pressurized. Third, the moisture breathing effect noted above is greatly aggravated during descent through cloud for equipment in non-pressurized sections of the aircraft.

### **Some Case Histories on Environmental Defects**

The following are some brief examples of defects in service electronic equipment arising from severe environmental factors.

#### *Vibration (Navigational Bombing System in 'V' Bombers)*

Several failures of the chassis of a particular unit, near a transformer mounting, occurred on one type of 'V' Bomber only. The failures from metal fatigue resulted from the vibration level at certain frequencies being far higher than was expected. The equipment was satisfactory in other 'V' Bombers<sup>(4)</sup>.

#### *Shock (In Beverleys)*

A common application navigational aid equipment was installed in the Beverley transport aircraft on a standard mounting tray. The tricycle landing gear of this particular aircraft produced persistently higher shock loadings than normal. In one instance, the tray structure failed and the unit came adrift<sup>(4)</sup>. There are no recorded instances of this type of defect for other aircraft application.

#### *Low Temperature*

##### *(a) In 'V' Bombers*

Owing to the increased altitude capability of later 'V' Bombers, the connecting cables to the H<sub>2</sub>S scanner, which are flexed by the Roll and Pitch stabilization, were subjected to lower temperatures than previously. Stiffening of the P.V.C. sheath and insulation occurred, resulting in early failure from cracking of the P.V.C. and abrasion of the screened cores<sup>(6)</sup>.

##### *(b) W.E.E. and Electronic Equipment<sup>(7)</sup>*

Few examples of pure electronic component failures have been found, but typically prominent defects were: N.S.F. toggle switches became too stiff to operate; wire wound resistors appeared to display a negative temperature coefficient; motors in the loop aerial of a Radio Compass seized, and many failures occurred of miniature valve in a Cloud and Collision Warning system.

#### *High Temperature (Navigational Aid in 'V' Bombers)*

CV 448 germanium diodes, used in a Doppler navigational aid, gave trouble after prolonged use

at high temperatures, owing to increased leakage current causing drift in d.c. amplifiers. It was necessary to replace the diodes by silicon types to achieve the required stability<sup>(6)</sup>.

#### *High Temperature*

In a mobile radar equipment deployed in the Far East, the RF Receiver waveguide switch jammed owing to differential expansion of the barrel<sup>(8)</sup>.

#### *Hot Damp Jungle Conditions (Equipments in F.A.R.E.L.F.)*

- (a) Serious difficulty has been experienced in keeping equipments serviceable owing to the high failure rate of Mk. 4B connectors. This is caused by moisture between the plug/socket interface and on the gasket, resulting in severe tracking and breakdown of insulation. Most failures occur with those connectors that have to be removed when the equipment is redeployed, often in pouring rain. As a temporary expedient, the rubber gaskets have been removed from some 80% of the connectors which are then liberally treated with MS4 silicon grease<sup>(9)</sup>.
- (b) Trouble has also been experienced with units overheating after the fan motors have seized up. This defect is caused by corrosion of the bearings after the grease has been dispersed by high temperature, and by corrosion of the rotor and stator pole faces<sup>(6, 9)</sup>.

#### *Driving Rain*

Heavy rain resulted in water leaking into a junction box on the aerial pedestal of a mobile radar deployed in Singapore. This caused severe tracking and breakdown of insulation<sup>(8)</sup>.

#### *Salt Corrosion*

Intermittent defects in the AI radar of carrier-based aircraft have frequently been traced to corrosion of the Mk. 4 plug and socket connections<sup>(9)</sup>.

#### *Driving Spray*

On a U.K. coastal site it was found that salt laden spray was being driven up over the cliffs at an angle of 20° straight into the ventilation louvres of a mobile equipment<sup>(9)</sup>.

#### *Contamination by Hydraulic Fluid*

Contamination of the pure air supply to an airborne missile was found on carrier-based aircraft, which would result in serious loss of performance. Severe impacts of deck landings caused leakage of hydraulic fluid from the nose Oleo system. As the pure air bottles were located in the same compartment, contamination of the air supply could easily occur when the air bottles were changed<sup>(9)</sup>.

#### *Miscellaneous Environment Factors*

The rubber hydraulic hoses driving a hydraulically operated AI scanner ran fairly close to the Rate Gyro of the aircraft Auto Pilot system. Under certain conditions of aircraft flight and scanner operation these hoses were deflected so that they just touched the casing of the Rate Gyro, completely upsetting the Auto Pilot system owing to the pulsations of liquid in the hoses<sup>(9)</sup>.

#### *Survey of Contemporary Solutions*

There are few simple problems in the design of military electronic equipment, even for "normal" deployment, and design for "extremes" largely becomes an extension in depth of the solutions to the problems which already exist. These are now discussed under the headings of:

Environmental Engineering  
Ergonomics  
Power Supplies.

#### *Environmental Engineering*

The overwhelming cause of unreliability is inadequate environmental engineering, and significant improvements could result from serious design attention, at least on a par with that given to performance, in this area. Put simply, environmental engineering may be defined as matching the intrinsic environmental performance of each component and assembly to the environmental conditions seen in the field. Expanding this oversimplification leads to four principal activities:

First, to understand the nature and effect of each environment and to determine the quantitative levels and the interaction of the various environments. The difficulties here have been indicated above.

Second, to design and build the equipment using techniques which alleviate or resist the appropriate climatic environments, so that the local working conditions for the parts (*i.e.*, materials, processes, components and circuit functions) are rationalized to a level below the known environmental limitation of the parts.

Third, to carry out systematic environmental tests throughout every phase of development because these tests represent a most powerful, and indeed the only, tool available to determine the potential weaknesses of the equipment and its ability to perform under extreme conditions.

Fourth, to ensure that the quality assurance activities during production, whether for parts, assemblies, or the finished equipment, are sufficient to maintain adequate copying standards of the models certified for Design Approval.

The first and second points may be taken together and covered by a discussion under three classes of environmental treatment, heat, isolation and endurance.

### Heat

All electronic equipments liberate heat within a local environment which either adds heat to, or extracts heat from, the equipment. The design problem is to achieve a heat balance such that at all times no part of the equipment is subject to temperatures above or below the rated limits for that part for performance, reliability and survival.

The local environment is created first by the heat at ambient air temperature, to which may be added solar heat, directly or indirectly, and also vehicle generated heat; interacting with these prime conditions will be the heat generated by the equipment. The distribution and values of temperature throughout the equipment will depend upon the heat exchange processes active between the parts, the equipment, and the final sink for heat gain or heat loss. The factors governing any heat balance, theoretical or practical, are very complex and it is not surprising that accurate prediction of the temperatures over which individual parts will range in the field is virtually impossible; coupled with this is a system of rating components for temperature which does not facilitate design for temperature extremes. The difficulties are self-evident.

The type of defect tendencies to be associated with temperature have already been indicated. It is worth emphasizing that there are two principal classes of defect due to temperature, one basic and one conveniently described as differential expansion. Also, that low temperatures essentially result in (generally unavoidable) functional defects of mechanisms and (apart from flexing cables) do not normally lead to catastrophic failure of components as does high temperature. Basic effects, such as loss of strength or deterioration of electrical or mechanical characteristics, may usually be anticipated from standard references and to some extent allowed for during design. In contrast, the detailed mechanism of the differential expansion defect is difficult to anticipate in magnitude; no assembly of parts whatsoever is free from this effect, which will always become a defect if the temperature excursion is large enough, and this is often the case in electronics. Experience, however, confirms again and again that both forms of defect disappear if the operating temperatures are rationalized. The characteristics of important present day electronic materials imply "ambient" temperature limits of about  $-25^{\circ}\text{C}$  to  $+60^{\circ}\text{C}$ —curiously, this roughly corresponds to the temperature performance of man himself!

Much vehicle, aircraft and missile equipment suffers from overheating tendencies (and sometimes overcooling), but in the author's view there is really no good reason why this should be so, for it can be shown that it is inadequate thermal engineering, not fundamentals, that is responsible. For

example, the arguments for liquid cooling aircraft equipment, or even ground equipment, are unassailable on theoretical and practical grounds, and indeed only liquid cooling has the necessary development potential for extremes. The real difficulty for temperature extremes is associated with highly mobile, or man-pack type equipments for ground use, and here we believe there is enormous potential in fluorochemical type cooling methods.

With this form of cooling the principle is to immerse the electronics in an inert liquid dielectric coolant in place of air. A range of fluids called fluorochemicals have so far become available, but either FC 75 or FC 43 is normally used, having the following properties:

Outstanding heat transfer capability, chemical stability and inertness, wide working temperature range, high density, high coefficient of expansion, low viscosity, low surface tension, low power factor and very high dielectric strength with resistance to corona breakdown.

These properties offer greatly reduced equipment bulk and weight, and increased reliability; this latter bonus arises because uncontrolled environmental conditions of temperature and humidity can be attenuated or eliminated, and because both the thermal stresses on components and hazards of high voltage circuitry can be substantially reduced.

The heat transfer efficiency of FC 75, even by natural convection modes in the liquid phase, is vastly better than that for air, and somewhat better than that for normal transformer oil. In contrast, however, boiling FC 75 will transfer at least ten times as much heat as transformer oil used in the natural convection mode at the same temperature, and transfer rates as high as four watts/sq. in./°F have been reported; this attribute alone provides a solution to the particular problem of high dissipation components. At the same time, all components, including microcircuits, are temperature conditioned by immersion, and protected from the potential degradation due to rapid temperature changes.

The fluorochemical only transfers waste heat to the container wall, and stabilized internal temperatures will depend on the quantity and temperature of the rejection heat transfer fluid available to the external surface. Normally, it is desirable that this will be air for ground equipment, because of the added burden of specialized heat rejection sinks.

The improved dielectric properties of liquid fluorochemicals permit close packing of components operating at very different potentials. Special components can be developed in some cases to take advantage of the dielectric and heat transfer properties, and lead to much smaller components having at least an equivalent performance to the conventional air cooled versions.

The designer then has the challenging opportunity (and problem) of reducing the overall size of the equipment, and achieving a high component packing density. Very substantial reductions have been realized for high voltage transmitter equipment, and the weight saving on the structure has more than offset the weight of fluorochemical needed.

The process is not without its engineering problems, particularly sealing, and repair maintenance is difficult, but the marked weight saving and increased reliability surely justify far more intensive development than hitherto on fluorochemical cooling.

#### *Environmental Isolation*

It was earlier suggested that the detailed environments covered by the classifications humidity, free water, dust and sand, and atmospheric pressure could all be designed out by the first need to exclude moisture, because the only solution to moisture degradation problems is isolation. This can be achieved either by sealing off the equipment contents or, for water vapour alone, by heating, but the latter would carry an electric power penalty which would be unacceptable for extreme conditions. The methods of sealing, range from pressurization, in which the interior of the equipment is kept filled with a dry gas, e.g., air, nitrogen, etc. a few p.s.i. above atmospheric pressure, to the encapsulation of parts in a rigid or flexible "pot" of dielectric material. This latter method has its best application in small assemblies containing no moving parts and very limited self-heat dissipation, but it adds weight (even if foamed material is used) and introduces defect liabilities due to shrinkage tendencies during curing and/or moisture ingress via the brought-out connections.

It follows that dry gas sealing will also isolate the other environments noted above, but the method has problems. There are three main variants of sealing and each depends upon the efficiency of all the boundary seals between interior and exterior of the equipment; anything less than properly engineered seals will lead to early failure. The highest protection is afforded by the fused, or hermetic, seal, but this becomes impracticable on volumes much greater than, say,  $\frac{1}{4}$  cu. ft. Next is the pressurized seal which may be either hand pressurized at intervals, or automatically held at some fixed pressure by a pump or storage cylinder. Finally, there is the plain sealed method, which has its main application in ground equipment but is of only limited use in aircraft. Here the equipment is contained within a box whose pressure is nominally atmospheric; it may be fitted with inward and outward pressure relieving valves, or a breathing-tube desiccator unit.

All three methods incur penalties. The hermetic

seal cannot be maintained in the field, but is thrown away or returned to the manufacturer. The pressurized sealed equipment is probably the most reliable system of protection and, up to a volume of, say, 2 cu. ft., it does not carry an added weight penalty. Above this volume, however, the problem becomes one of pressure vessel design, and weight and cost will soar. The principal drawbacks to the method are the need to monitor the pressure regularly, the need to have access to leak measuring and leak locating test equipment, and to have repressurizing apparatus, preferably with dry gas, in the field. The objection to plain sealing is that the liability to substantial internal temperature changes and/or carriage by air means virtually designing for the pressurized seal method but without gaining the advantages. In the breather-tube desiccator variant, one is never quite sure how dry is the internal air and, moreover, no one seems to understand fully exactly how the breather-tube mechanism works—we have conducted limited experiments in which the maintenance of a dry or damp atmosphere within an equipment seems to be purely chance.

So far we have considered pressurization in rather general terms and applicable to pieces of hardware manageable by one, perhaps two, persons. When confronted with a portable or mobile installation, sealing out the external environment becomes of less interest than sealing in a conditioned environment, but if air-conditioning has to be provided this creates not so much a technical problem as one of supplying enough power to operate the air-conditioning apparatus.

The ancillary, if not greater, problems of isolation fall upon the connectors and cables linking one equipment to another. Under extreme conditions the sealing of these components often causes more trouble than in any other area. If the cables do not crack at temperatures as mild as  $-30^{\circ}\text{C}$  they may well serve as biological food, or the connectors may be contaminated with moisture, or mechanically damaged.

#### *Endurance*

The environments largely representing endurance problems are corrosion, wind and ice. Of these, corrosion need not present any serious problems since it is a matter of selection of the correct protective finishes; corrosion does indirectly reflect the problem of weight, because magnesium alloys cannot be processed for anti-salt corrosion, precluding the use of a material half the weight of aluminium.

Surface winds at maximum severity are unlikely to present an economic design objective for survival; one is all too familiar with the damage potential of typhoons and hurricanes, and the problem is to decide on an acceptable severity level

since there is no real basic design difficulty in the necessary structures. Design for function under extreme wind speeds is another matter, which primarily concerns aerials. The problems may not be intractable, but the higher the wind the heavier and more costly the structure, and in the case of rotating aerials, the more difficult the response control problem and the greater the electrical power required to drive and control. Wind at altitude is not discussed here.

On the matter of ice, there is generally little that can be done other than to determine the limiting thickness at which the exposed moving parts, or aerials, fail to function and to apply a removal drill in the field. The fact that even a thin ice build-up soon nullifies propagation from aerials and radomes presents virtually an insoluble problem before other icing elsewhere matters.

The remaining environments, snow, hail and thunder, may be treated primarily as propagation problems; they do not present particular design problems for extremes. The snow load on aerials for survival can be determined. Surface hail occurs so infrequently it might reasonably be ignored; hail in flight is a totally different matter and is not dealt with in this paper.

#### *Ergonomics Potential*

Weight, bulk, ease of use, ease of repair:—It is impossible to reduce these factors to simple problems. Consciousness of the weight problem became apparent two decades ago by the introduction of the miniature valve, followed rapidly by the subminiature valve. From these stemmed miniaturization of many associated electronic components and processes—for example, the high stability resistor, the high-K capacitor, C-core transformers, ferrites, printed wiring, film resistors. The technology of electronic solutions to problems has gone forward in seven-league boots, but complexity and unreliability have overtaken both the limited gains realized from early miniaturization and the enhanced reliability that might well have matured from a period of stable development on miniaturized techniques.

We have tried to show that the operation of electronic equipment under extreme conditions can be reduced to the environmental problems of heat, isolation and endurance, whose magnitudes are governed largely by the ergonomics of contemporary electronic techniques. These provide a solution to the basic fundamental problems of navigation, search, computation, identification and communication on land and sea and in the air, a solution not possible by any other method, but electric power is utilized at very low efficiency. This penalty is aggravated by the added weight and bulk penalties arising from the need to provide environmental protection for the already dispropor-

tionate weight and bulk of the electronic equipment. These penalties have become grudgingly acceptable for military electronic equipment for normal deployment but, under extreme conditions, ranging from man in tropical jungle to man in a Mach 3 strike aircraft, weight becomes a convenient common indicator to the size of the problem.

Reduce weight and the deployment problem under normal or extremes is reduced because supply and maintenance logistics, manning, and power supplies are all reduced. Significant weight reductions can only come from either much less stringent staff operational requirements or from the intensive development of microelectronics.

#### **The Significance of Microelectronics**

Microelectronics, or integrated circuits, can be considered a logical development of miniature and subminiature electronic equipment commencing with the introduction of the transistor in 1948. As conventional tubular components were made smaller and smaller to be compatible with the physical size of the transistor, the separation of the useful element, *i.e.*, the thin film, from the carrier element, *i.e.*, rods, *etc.*, by deposition on one substrate, became the first type of thin-film circuit. In parallel, the improvement in semi-conductor device technology led to the introduction of resistive regions utilizing the resistivity of the material, and capacitive regions using depletion layer effects. Microelectronic techniques are concerned primarily with low power devices, and, in general, any low power equipment which can be transistorized can be micro-miniaturized. "Microelectronics" has been defined internationally as assemblies with a density greater than 50 parts per cu. in. or 3 per cu. cm., and there are three main subdivisions of microelectronics in micro-assemblies, thin-film and semiconductor integrated circuits.

Thin-film integrated circuits can be subdivided into those with attached transistors and diodes and those with evaporated active devices (experimental at present), whilst semiconductor integrated circuits can be either single or multi-chip devices. Hybrid circuits can be made of any combination of micro-assemblies or integrated circuits.

Microelectronic circuits are packaged into sealed flat units approximately  $\frac{1}{4}$  in.  $\times \frac{1}{8}$  in.  $\times \frac{1}{16}$  in. or in cylindrical units approximately  $\frac{1}{4}$  in. diameter and  $\frac{1}{4}$  in. deep. These units are then assembled into equipments.

The main advantages of microelectronic assemblies are:

- (a) Improved reliability over conventional assemblies—resulting in less maintenance.
- (b) Reduced weight—the importance of this has been previously discussed.

(c) Reduced size—enabling them to withstand higher shocks and accelerations.

There are many other advantages resulting from their small size. Redundancy techniques can be fully utilized enabling still higher reliability to be realized. The number of interconnections has been greatly reduced and therefore higher reliability is obtained over conventional assemblies. Some problems remain over achieving an extremely high reliability standard with the few connections still necessary. The power required for these circuits is also reduced, particularly with MOST (metal oxide semiconductor transistor) circuits.

It is possible to replace the transmitter magnetron in radar equipments by using a large number of semiconductor integrated circuit oscillators in parallel, and circuits have been designed to produce 50 kW at 'X' band. The mechanically rotating aerial can also be replaced by similar units arranged as beam swinging phased arrays.

All these advantages over normal transistorized constructions mean that the problem of environmental protection is greatly eased, and the hope of designing fully engineered electronic equipments capable of withstanding extreme environmental conditions can only be fulfilled in the future by the use of microelectronic equipments.

Some impression of the enormous benefits from reduction of weight, bulk and power from micro-electronic techniques are illustrated in Fig. 2, which shows a density increase from one part per cubic inch in 1940 to several thousand per cubic inch in 1966.

### Conclusions

This paper has attempted to show that the obstacles to the deployment of equipment under extreme conditions are essentially ergonomic. In the development of a project the shortage of scientific and engineering staff, both at contractors and in R & D organizations, naturally results from the overwhelming attention being given to the achievement of a working solution to satisfy the Military Requirement. Thus, ergonomic factors such as weight, size, maintainability, and reliability do not receive the attention they warrant and therefore the solution to the problem of equipment design for extremes lies mainly in project management.

No new technical problems arise in the design of electronic equipment in extreme conditions, only more intensive research in three broad areas:

- (a) An adequate definition of "extreme conditions" in a form which can be translated into engineering terms. This particularly concerns the probability of man's deployment during the probability of occurrence of the "extremes", man's performance, and the time (cumulative or continuous) for which man and the equipment must be reliable.
- (b) The equipment deployment problem is diminished with a reduction in weight of say an order of magnitude. Here, immediate potential exists in hybrid-transistorized techniques but the real answer lies in the application of microelectronics, which also offer a higher reliability potential.
- (c) The need for improved auxiliary power supplies exists in parallel with the need for miniaturizing techniques, but power supply and maintainability problems also reduce in scale with the use of microelectronics.

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- (1) "War Department and Ministry of Aviation". Standardization Design Memoranda No. 89, 1963.
- (2) "Human Engineering Guide to Equipment Design". Morgan, Cook, Chapani, Lund. McGraw Hill, 1963.

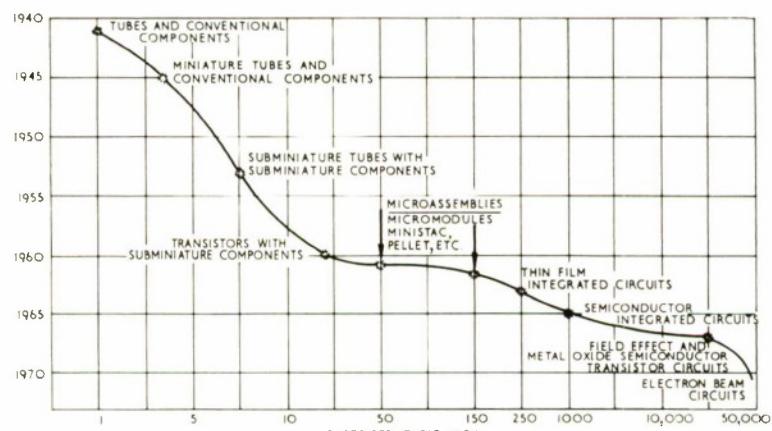


FIG. 2. Electronic miniaturization over 25 years.

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## APPENDIX 1.

### Electronic Equipment Design for Extreme Climatic Conditions

#### *Estimation of Environmental Severity Levels*

Until 1961 the design levels for natural environments were largely confined to temperature, humidity, pressure and wind and stemmed from a scattered collection of official requirements reflecting differences between the three Services, Defence and Aircraft Ministries. Often the requirements for temperature and humidity were quoted, not in terms of basic design levels but in terms of test levels to be met by demonstration. In 1961 the War Office published the report of its working party on the probable extremes of air temperature, humidity and solar radiation and this voluminous report was later rationalised into SDM(L)89/3<sup>(1)</sup>, the present day official standard for these environments. In the late '50s an M.O.A. Joint Design Requirement Committee (JDRC No. 2) commenced work on the preparation of an environmental handbook<sup>(3)</sup> for G.W. purposes with terms of reference to cover not only the entire range of natural and self-generated environments, but the associated problems of design and test. This handbook is progressing well and because it has adopted a statistical presentation of basic data wherever possible it is not unique to the G.W. areas, but probably applicable to any military equipment. Much of the material in this appendix is derived from Ref. <sup>(3)</sup>.

#### *Temperature*

SDM(L)89 Issue 3<sup>(1)</sup> defines two standards, "Normal" and "Severe Cold". The former ranges in air temperature limits from 70°C to -36°C with an assumed zero wind speed; the latter in limits from (presumably) 70°C to -62°C, the low temperature being qualified to -57°C with a wind speed up to 15 knots. The Normal case is presented in terms of a diurnal variation and both Normal and Severe Cold are modified according to whether the reference temperature is shelter-storage or open-exposure. The Normal case is clearly presented on a 1% risk basis *i.e.* only on three or four days in the year are the values likely to be exceeded but the risk is based on the probability (to what confidence levels is not given) of occurring at all, as opposed to the time period during which such levels will be exceeded. In several ways the information given is confusing and it is necessary to refer back to the original work data.

A new presentation of basic data has been adopted in Ref. <sup>(3)</sup> in which air temperature is considered a random variable with a normal distribution up to at least two standard deviations; at three S.D.s there is some uncertainty about the

distribution remaining normal and error or close agreement with recorded extremes may be found. Fig. 1 shows the distribution of mean annual temperature at sea level for much of the world and Fig. 2 shows the standard deviation for its long term mean; detail charts exist for the arctic regions. With this presentation it is more convenient to describe the temperature risk in percentiles; by this is meant the percentage of time for which a given temperature is below or above a certain value. The generic 1% risk limits mean the upper and lower one percentiles which correspond to that temperature which is not exceeded, and that temperature which is exceeded, for 1% of the time. For a given locality 1% values are determined by adding or subtracting 2·35 standard deviations on the mean. Moscow at 1% has recorded limits of +28°C and -23°C over a five year sample whereas from Figs. 1 and 2 the limits are +32°C and -23°C; for the extreme limits ever recorded the figures over 67 years are +36°C and -34°C and may be compared with 0·5 percentiles which from Figs. 1 and 2 translate into +47°C and -35°C. The tendency to close agreement in the lower temperature and over-estimation of the upper limit is a common feature of the data derived from Figs. 1 and 2 and implies insufficient refinement of the distribution characteristics.

Air temperature may exhibit a steady and regular variation throughout 24 hours, generally described as diurnal, and although irregular and large occasional changes occur these are usually averaged out if sufficient number of days are considered. The maximum diurnal swing in temperature for most practical purposes is about 20°C in the open and 40°C in certain sheltered conditions. Certain climatic conditions such as strong radiant cooling with no wind, or when a land wind is replaced by a wind from the sea, or during thunderstorms in very hot weather, promote exceptionally large changes of air temperatures in short periods and for equipment design purposes these constitute defect promoting environments in the category of extremes. Typical recorded rises are 27°C in two minutes at Spearfish, Dakota and 20°C fall in five minutes at Port Nolloth, South Africa.

In considering extreme temperature conditions the identification of what we mean becomes difficult because the man/machine interface intrudes. An aircraft, ship or tank will afford protection for the man from the external environments of the vehicle, although the temperature/humidity environment inside the vehicle may be onerous, whereas man exposed is limited by his metabolism via any protective clothing. For man exposed to indoor environments there exist physiological

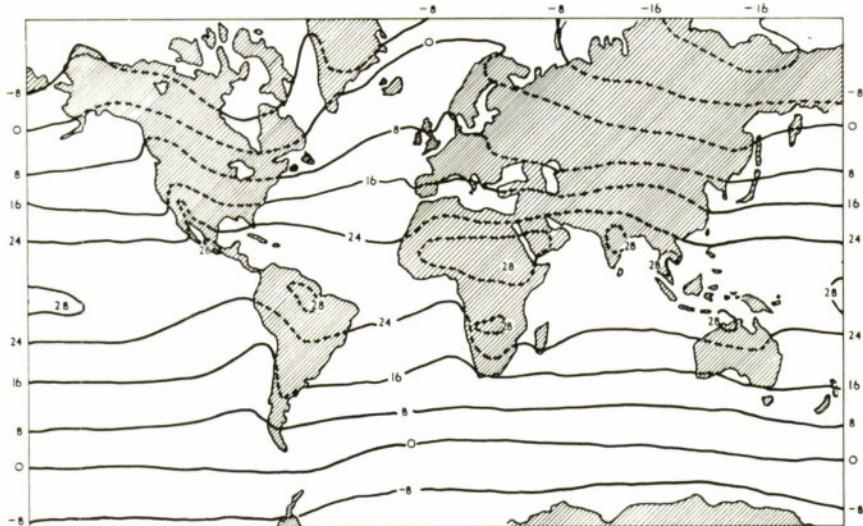


FIG. 1.  
Mean annual  
temperature °C.



FIG. 2.  
Standard deviation  
from mean.

scales of temperature<sup>(2)</sup> which, taken in conjunction with related humidity levels, provide an "equivalent", or comfort, range of temperatures over which man's efficiency at work remains sensibly stable.

Numerous experiments have been performed<sup>(2)</sup> and much investigation goes into man's ability to perform under, or resist extreme conditions of temperature and humidity<sup>(7)</sup> but the subject cannot be developed here. A brief comparison of extremes is given below.

Extremes, physiological for one hour<sup>(7)</sup>  
-72° to +64°C @ 10% R.H.

Extremes at 0.1% risk  
-64°C to +55°C

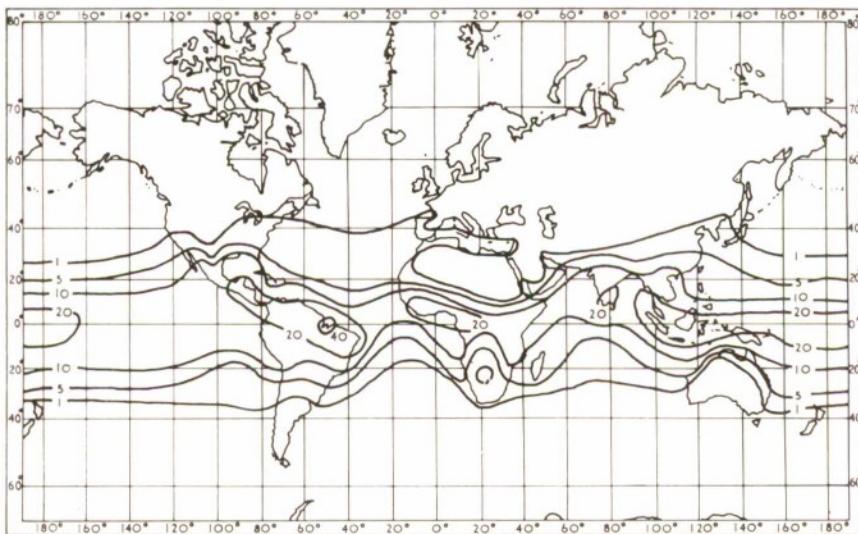
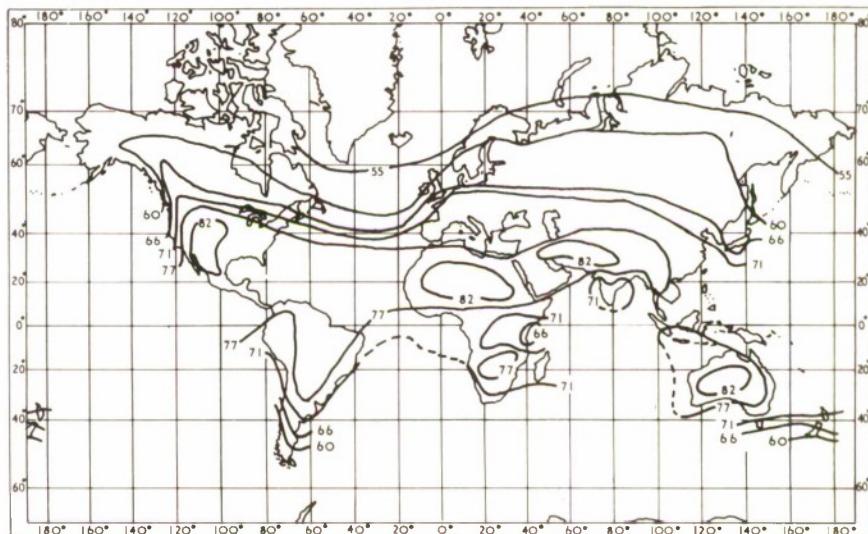
Extremes at 1.0% risk  
-57° to +52°C

Extreme limits recorded  
-69°C to +58°C.

#### Solar Heating

The temperatures so far discussed are air temperatures. In the design of equipment the influence of solar heating on the heat balance becomes significant, but insufficient data has become available on which to prepare a statistical distribution chart analogous to temperature in Figs. 1 and 2. The intensity of solar heating at a given point is dependent upon the solar constant, the earth's solar distance, the attenuation in the atmosphere, the latitude and the amount of scattered radiation

**FIG. 3.**  
Estimated distribution  
of maximum temperatures  
(°C) of non-conducting  
surfaces exposed  
horizontally to the Sun.



**FIG. 4.**  
Estimated percentage  
frequency of time  
temperature  $\geq 20^{\circ}\text{C}$ ,  
and relative humidity  
 $\geq 90\%$  during the year.

received as sky radiation. Assuming constant atmospheric conditions there will be a diurnal variation of intensity, and of course a marked seasonal variation. In translating an intensity value into the heat balance design it is also necessary to take into account the nature of the equipment surface and the local environmental conditions.

Fig. 3 illustrates the distribution of maximum temperatures which would be attained in an average year by non-conducting surfaces exposed normal to the sun. It has been extracted from Ref. (6) and is based on the mean annual maxima of shade temperatures and black-bulb readings.

It has long been assumed that clear skies offer a shorter risk than 1% and until recently there

had been no great pressure to take a diurnal variation into account; the design requirements are established at the maximum intensity of 200 CHUs/ft<sup>2</sup> hour, this severity being extended over some five to six hours. The requirement results in a degree of overtesting and is open to criticism where components of marginal performance in the region 60°C to 70°C are concerned. The criticism is fair and is directed at the difficulties of simulating the solar spectrum, especially if attempting to vary the intensity, or to apply a step function application during test simulation. In terms of "extreme" conditions it would seem that the existing requirement already covers solar radiation.

### Humidity

This is a general term describing the water vapour content of the air which exists in free molecular form as long as the air is clear; when in fine droplet suspension it is known as fog or mist. Humidity is expressed in many ways but for our purpose the most convenient is per cent relative humidity (R.H.) or vapour pressure. Generalizing in terms of human efficiency or equipment defecting tendencies, one is primarily interested in the bands 0 to 20% R.H. and 70 to 100% R.H. For the defect mechanisms aggravated by vapour pressure it is the combination of temperature with humidity giving the highest vapour pressure which is important.

The amount of water vapour in the surface atmosphere varies according to geographical location, season, time of day, moisture in the soil, precipitation, air temperature, air movement and terrain. The world extremes of absolute humidity (*i.e.* the mass of water vapour per unit volume) occur in the coldest polar and hottest tropical regions. Specific humidity (*i.e.* weight of water vapour per unit weight of moist air) is greatest over the equator and decreases towards the poles, being highest in summer and lowest in winter. The world's surface humidity has a geographical distribution for relative humidity different from that for specific humidity. It is highest at the equator decreasing from the middle latitudes; from say 30° latitude towards the poles the R.H. increases as a result of decreasing temperature. The seasonal distribution of R.H. also varies with latitude. From 30°N to 30°S the average R.H. is higher in summer than in winter, while at higher latitudes the reverse occurs largely due to low winter temperatures.

Persistent extreme humidities above 90% R.H. occur, sometimes for months on end in the rain forests especially in equatorial regions. Very low extremes of R.H., say below 5%, occur as surface humidities, only for periods measured in hours and in deserts where the air temperature is very high; at high altitude R.H.s lower than 5% are persistent and common but will be associated with very low temperatures. In terms of extreme vapour pressures these are markedly influenced by the containment of humid air under near-stagnating conditions such as temporary shelters. The average extreme vapour pressure in the open is, on say a 1% risk, about 16 in. to 18 in. S.W.G.<sup>(1)</sup>. Construct a temporary shelter and the vapour pressure not only doubles but exhibits a marked diurnal variation with its maximum during late morning.

A vast amount of basic data exists for certain areas but the difficulty is the applicability and/or presentation of the data, especially where the two

parameters of temperature with humidity are to be associated with time periods. Detailed histograms become somewhat impracticable but within limits it is possible to plot world distributions of the percentage of time that significant combinations of high humidity and temperature have been exceeded in the surface atmosphere; Fig. 4 is a typical world yearly isopleth for temperatures greater than 20°C and R.H.s greater than 90%. The occurrence of extremely low humidities are, at high altitude, sufficiently stable to ignore statistical distributions, moreover the water content is so low that relative humidity is not meaningful. On the ground, too little data exists.

Fig. 5 shows information gathered together to provide a maximum R.H./maximum temperature curve and superimposed are two reference levels of constant absolute humidity, 32g/m<sup>3</sup> and 10g/m<sup>3</sup> and it is suggested that the envelope so formed offers a reasonable design case embracing all extremes from +52°C to +30°C. Fig. 6 suggests the comfort and danger zones of man's physiological limits. The very great difficulties that the white man experiences in humid conditions when the wet bulb is above 25°C are well known and although experience in the last war indicated that this limit may be raised a few degrees, the absolute limit seems to be a wet bulb of about 29°C for anything other than very light short-term work or mental effort.

We should perhaps admit that given quantitative data on humidity it is of little value in the design of most equipment because the state of the art is such that every effort must be made to isolate humidity. Probably the only applications for which quantitative data is necessary are those concerning man, air-conditioning and air-breathing engines. Summarizing on a 1% risk basis:

+37°C can be associated with humidities of 60% to 65%

+25°C can be associated with humidities of 95% to 100%

Highest vapour pressure in the open 16 in. S.W.G.

Highest vapour pressure in storage 32 in. S.W.G.

Lowest R.H. on surface (at +52°C)  
10% approx.

Water content at altitude (45,000 ft.)  
0.002 lb. water/1000 lb. air

Highest constant specific humidity at ground level (equivalent is 100% R.H. at 30°C) 0.025 lb. water/lb. dry air

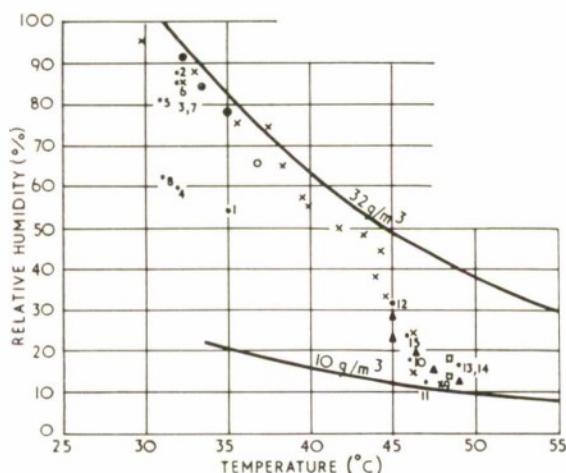


FIG. 5. Maximum recorded temperature/humidity conditions compared with absolute humidity curves.

- |     |                         |  |
|-----|-------------------------|--|
| x   | Dhahran                 | } from examination of<br>meteorological office records |
| ○   | Bahrain                 |  |
| △   | Habbaniya               |  |
| □   | Shibah                  |  |
| .1  | Khartoum                |  |
| .2  | Singapore               |  |
| .3  | Hong Kong               |  |
| .4  | Cairo                   |  |
| .5  | Gan                     |  |
| .6  | Karachi                 |  |
| .7  | Darwin                  |  |
| .8  | Sydney                  |  |
| .9  | Idris                   |  |
| .10 | Sharjah                 |  |
| .11 | Kufra                   |  |
| .12 | Tucson Las Vegas Dallas |  |
| .13 | Habbaniya               |  |
| .14 | Shaihah                 |  |
| .15 | Dhabran                 |  |
- (from information supplied by meteorological office)

### Wind

Information is far from complete and most data has accrued from the sea areas used by ships. Wind speed is classified according to its mean velocity which is averaged over a period of 5 to 10 minutes, the basis employed in the preparation of the Beaufort Wind Scale. An additional quality of wind speed is the "Gustiness Ratio" (G.R.) which is the ratio of maximum gust velocity to the mean wind speed and is a measure of the gustiness of winds flowing from the same direction. A gust is a transient velocity measured over a few seconds. Generally, the G.R. will be between 1.2

and 2.0 with an average value of about 1.5 in open country but nearer to 2.0 in built up areas.

The variation of wind with flight altitude is too highly specialized to discuss in this paper, it being a subject of importance to missile and aircraft designers. The influence of topography on wind speed can be considerable and special winds occur in mountainous country having close proximity to the sea where great height and substantial temperature differences exist within relatively short distances. Examples of these winds are the bona, the mistral, the borg and katabatics of the Antarctic. Very severe winds accompany tropical cyclones which fully developed may extend to above 130 knots.

For design purposes wind speed is most usefully presented as a percentage frequency of occurrence during an average year when the mean velocity is greater than a given value, and Fig. 7 shows a global plot for surface winds of whole gale force *i.e.* greater than Force 10 (48 knots). Also to be taken into account is the gustiness and Fig. 8 shows the maximum gust velocity likely to occur once in 10 years. These figures are applicable to open area and cannot take into account topographical influences.

The definition of extreme conditions for wind may be very much qualified for operations, by the maximum wind plus gusts which man can endure unprotected. For survival, economic considerations are the limiting factors.

### Rain

Rainfall measurements are normally confined to the average monthly and annual totals, the average number of days upon which rain falls and possibly the maximum in any 24 hour period. Frequency and intensity duration do not seem to be generally available. Three types of rains are recognized, orographic, cyclonic and convectional, each being defined by the cooling mechanism which leads to cloud formation. In this paper we are probably interested only in the rate, or intensity, of rainfall and not the total accumulation,

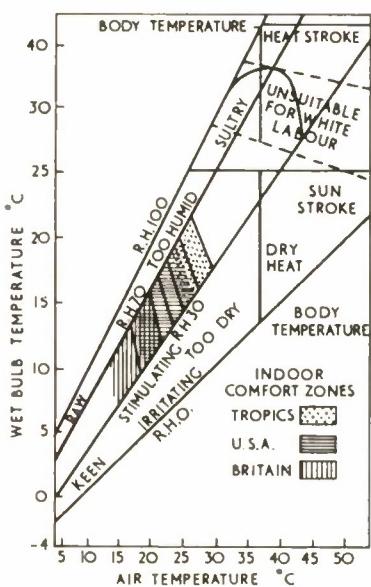


FIG. 6. Comfort and danger zones.

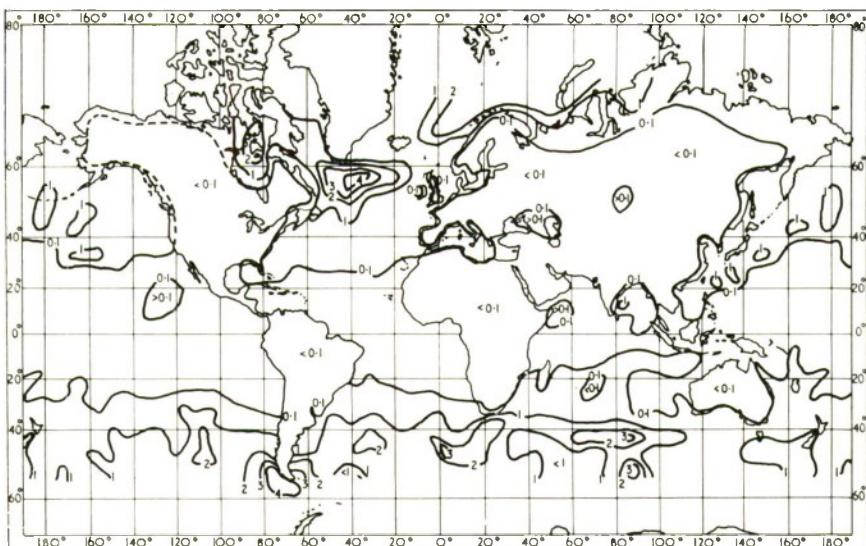


FIG. 7.  
Percentage frequency of  
winds  $\geq$  Beaufort Scale 10  
( $\geq 48$ kts).

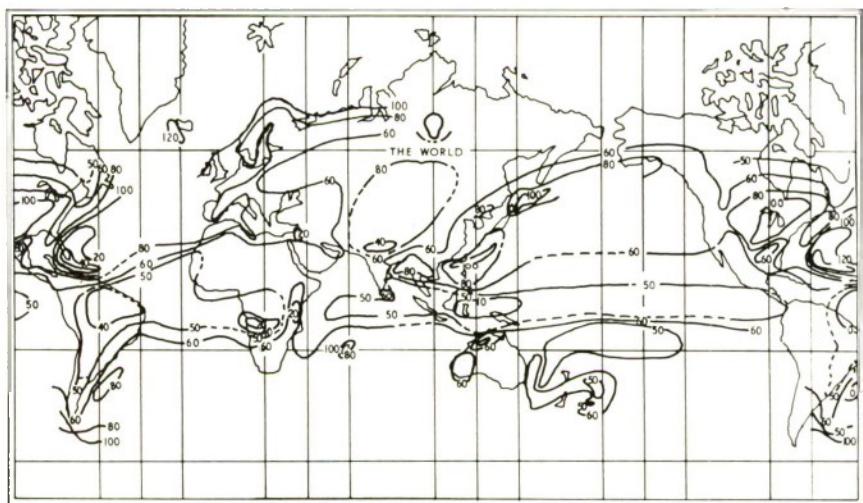


FIG. 8.  
Maximum gust  
velocity likely to be  
experienced once  
in 10 years (Kts)

since the equipment problem for rain is not a survival problem. Conventional rains are essentially thunderstorms and have a high intensity.

Thunderstorms occur most frequently in equatorial and sub-tropical areas, usually over land or coastal waters. The arid sub-tropical and the polar regions are areas where thunderstorms are very infrequent, but even so there is still rather less than a 1% risk of occurrence in these areas. Over most of the world's surface the risk is at least 3% increasing to some 50% in the equatorial regions of land masses. Thunderstorms are not of course measured in quantitative terms and the enormous amount of data on rainfall coupled with the various mechanisms of equipment defect

associated with rain and thunderstorms make it virtually impossible to give a summary on extreme cases. The table which follows suggests near-maximum intensities applicable on a very broad climatic zoning.

The size and terminal velocity of raindrops may be touched upon because of their influence on propagation and radome erosion. Raindrops cannot grow to greater diameter than about 6 mm. since they then flatten and divide into smaller drops due to the resistance of the air. The greater proportion have diameters around 2 mm. but in thunderstorms may be as high as 5 mm. The free-falling speed of a raindrop will increase until the air resistance matches the weight of the drop at

Climatic Zone	Rainfall Intensity			
	mm in 1 min.	mm in 10 min.	mm in 1 hour	mm in 24 hours
Equatorial and sub-tropical regions (except sub-tropical arid regions)	18	75	200	400 to 800
Temperate climates (treated as a whole)	9	40	100	200 to 400
Arctic regions	5	15	40	75 to 125

which point the drop falls at uniform speed known as the terminal velocity; the following table indicates the relationship:

Drop Diameter (mm)	Terminal Velocity (cm/sec.)
0·1	27
0·5	206
1·0	403
2·0	649
3·0	806
4·0	883
5·0	909
5·8	917

Finally to sketch in extreme cases of mean annual rainfall of the order 5000 mm. or more, we can include Burma, East Pakistan, India, Java, New Guinea, New Zealand, Nicaragua, Cameroons.

### Snow, Hail and Ice

The heaviest falls of snow are likely to occur in the following instances:

- (a) Over land areas adjacent to the seas where comparatively mild air masses are brought into contact with cold continental air masses.
- (b) Where a cold unstable air mass penetrates over a warmer sea resulting in the formation of large convection cloud which may later move inland.
- (c) Where orographic effects are prominent; for instance snowfall under the conditions of (a) and (b) is likely to be greatly increased when the precipitating air mass is forced to ascent over high ground.

In general the interior areas of large continents do not experience high rates of snowfall although that which does fall may be for a long period. In mountainous regions, such as those of the Northern U.S.A., snow accumulates to an extreme depth of some 12 ft. and averages nearly 600 in. annually. For a highly compacted snow this represents a snow load of some 350 lb. per sq. ft. on the ground. Since snow must be endured, or isolated from an operational equipment, the

lack of quantitative data presents little real problem except to the structure designer who already works to an accepted maximum snow load equivalent to some 40 lb. per sq. ft. Snow may generally be expected when the temperature is below approximately +2°C and localities may therefore be roughly anticipated by estimation from world temperature charts as discussed above.

Hail is believed to be a constituent of all thunderstorms and since some hail is likely to melt as it falls it may not reach the ground as hail. Hail reaching the surface has a maximum occurrence in middle latitudes of five to 10 storms a year in continental areas and some 25 to 30 over parts of the ocean. Hail is rare in both polar and tropical regions despite the high thunderstorm frequency in the latter. The average duration is about seven minutes but extreme durations of 45 minutes have been recorded. Data on hailstone sizes, intensity and hailstorm occurrences is not available in a form suitable for statistical presentation. The size of a hailstone normally varies from 0·05 in. to 2 in. diameter, and extreme cases of stones as large as 5 in. to 6 in. diameter reaching the ground have been recorded but there is some theoretical justification that this is the largest possible size. The shape of a hailstone is mostly spherical but most shapes other than plane solids have been observed. Hailstorms at altitude is a specialist subject of great concern to aircraft designers, and it is not possible in this paper to suggest an "extreme" condition.

Ice, other than frozen water, occurs mainly as natural accretions manifest as hoar frost, rime and glazed frost. Hoar frost is a feathery deposit of ice crystals that form when water vapour at a temperature above freezing condenses on surfaces whose temperatures are below the freezing point; it normally occurs only in clear air *i.e.* on surfaces cooled by radiation. Rime is formed when drops of water at a temperature below normal freezing point, freeze on contact with a surface below freezing point. At ground level rime is formed in freezing fog or cloud and grows to windward; the extent of the accretion depends upon wind speed, time of exposure, amount of free water, drop size and aerodynamic flow—under severe conditions the object may accrete several feet. Glazed frost, also termed black ice, is a smooth layer of transparent ice, which forms when supercooled rain or drizzle falls on surfaces at or below freezing point; such ice is tough, difficult to remove and may attain considerable thickness.

Between latitudes of 30°N and 30°S icing, apart from hoar frost, is rare but will occur at times in cloud on higher ground; north and south of these latitudes the frequency of occurrence will increase with increasing latitude. Prolonged icing is most

likely in mountain ranges particularly where winds off the open sea cause large deposits of rime ice to accumulate; typical are the mountains of W. Scotland, W. Norway, W. Japan and Greenland. Icing at flight altitudes, as opposed to terrain altitudes, is again a specialist problem in need of no further comment in this paper.

#### Dust and Sand

The problem of dust and sand (D & S) is not necessarily peculiar to arid deserts but can arise whenever high solar radiation and low rainfall are combined with erosion of soil. Dust is defined as particulate matter of size 1 to 150 microns while sand describes loose, unconsolidated, accumulation of detrital sediment consisting essentially of quartz grains of size 100 to 1000 microns. The intensity, or concentration, is measured in terms of the weight of D & S per unit volume and a D & S environment is defined by this, by the particle distribution characteristics of size, shape and material, and by the wind velocity.

The concentration of D & S in the atmosphere varies with geographical locality, local climate and the full range of natural D & S falls into three categories: Instantaneously Airborne, comprising pebbles and the larger dust sizes activated by artificial means such as vehicle and aircraft propulsion exhausts. Temporarily Airborne, raised by artificial means but also by high velocity winds; the particle size will lie between 2 and 150 microns and the settling velocity is low so that the dust remains in suspension in the air for a considerable time. Permanently Airborne, describes D & S below 2 microns in size with a settling velocity below 0·06 f.p.s.

Particle size distribution may be defined on a percentage weight or count basis and a common method is assessing the percentage weight of particles which will pass through sieves of various mesh sizes. Fig. 9 illustrates particle size distributions of road dust from abroad. Studies of the vertical distribution of wind-blown D & S indicate

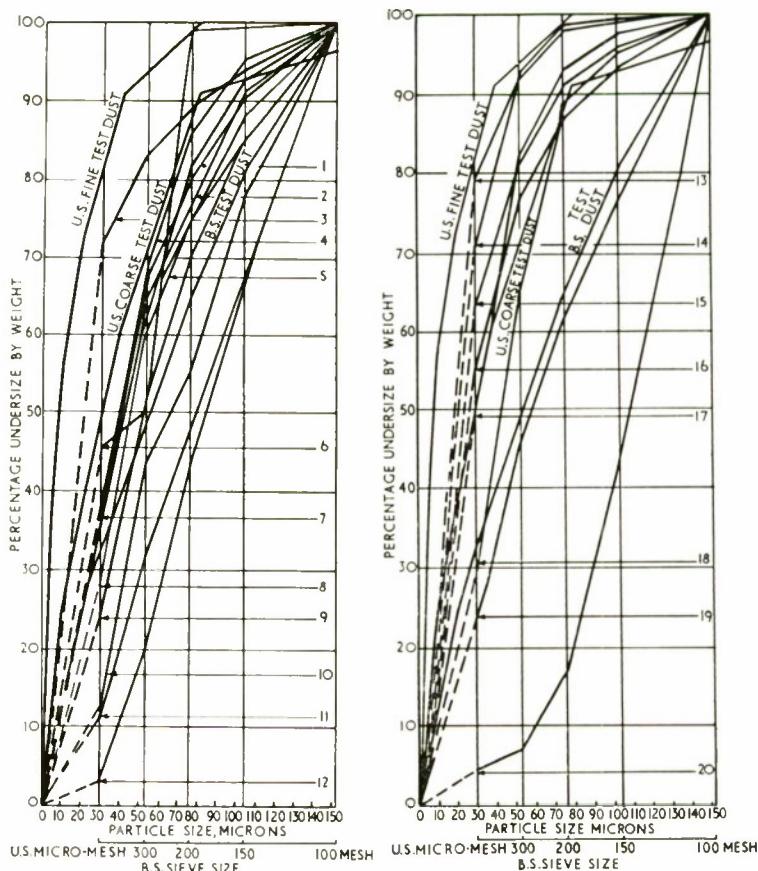


FIG. 9. Particle size distribution of dusts.

Particle-size distribution of standard dusts and dusts removed from used paper elements received from abroad.

#### Dust No. Country

- 1 New South Wales, Australia.
- 2 Nairobi, Kenya.
- 3 Rangoon, Burma.
- 4 Jos, Maiduguri, Northern Nigeria.
- 5 Mexicali, Mexico.
- 6 Lagos, Nigeria.
- 7 Gippsland, S.E. Victoria, Australia.
- 8 Maiduguri, Northern Nigeria.
- 9 Tijuana, Mexico.
- 10 Safat, Kuwait.
- 11 Cunnamulla, S.W. Queensland, Australia.
- 12 Canada.

Particle-size distribution of standard dusts and dusts received from abroad.

#### Dust No. Country

- 13 Buenos Aires, Argentina.
- 14 Enugu, Nigeria.
- 15 Addis Ababa, Abyssinia.
- 16 Tarkwa Dunkwa, Ghana.
- 17 Cordoba, Argentina.
- 18 Karachi, Pakistan.
- 19 Dorrigo-Bellingen, N.S.W., Australia.
- 20 Longreach, Central W. Australia.

that 95% of the weight of particulate material is carried within the first 10 in. above ground level. Smaller particles of less than 10 microns may rise to 5000 ft. but the upper limit for dust seems to be about 10,000 ft.

For a moderately dense dust storm, wind 25 knots, the density up to say 1000 ft., is approximately 0·5 mg/cu. ft. Little or no information exists from which to suggest extreme conditions but once in 10 years D & S storms of wind velocity 60 knots gusting to 80 may be anticipated in the deserts of N. Tripoli and Arabia.

### *Maritime Corrosion*

The atmosphere over the open sea and coastal areas is predominantly saline of high corrosive potential in a number of materials used in military equipment. Salt-laden winds will also carry measurable quantities of salt 20 to 30 miles inland in tropical areas, and in arid desert regions where precipitation is rarer, fine salt becomes admixed with dust and sand and carried as much as several hundred miles inland.

The constituent parts of a salt/atmosphere are approximately equal in proportion to those found in the sea, and the concentration level influenced by the degree of atmospheric evaporation of sea water and upon such dispersion factors as wind. Extreme concentrations are found in sub-tropical regions subject to high evaporation.

### *Biological*

The risk of biological attack is universal. Micro-organisms such as fungi and bacteria attack by chemical and soiling effects whereas insects, rodents and marine borers all attack by mechanical damage. Apart from the smaller insects the problem of mechanical attack is probably secondary to that of fungi and bacteria because under "extreme conditions" one might reasonably expect to be aware of the larger insects, rodents and other visibly-destructive pests. Fungi, unlike plants, contains no chlorophyll, and their food is derived from the substratum on which they grow but this food is absorbed only if in solution. Hence a stagnant and sensibly constant humidity close to saturation is vital for their reproduction and growth. With the plant kingdom there are estimated to be 100,000 known species but only a handful of these present problems to the equipment designer. There are no known "extreme" conditions for either fungus or bacteria; to design out one fungi properly is to cover them all and bacteria falls into the same design activity. As far as insects are concerned, again it would be difficult to define extreme con-

ditions; as with fungi, avoid the conditions which promote food and avoid certain woods, paper, rayon and other cellulose derivatives, or at least in a form attractive as food, and the problem is largely designed out, in so far as it is practicable to anticipate this problem.

### *Altitude Effects*

Little specific mention of the influence of altitude on a given environment has been made in the foregoing in order to keep the subjects as brief as possible. It is well known that the first relationship with altitude is that of atmospheric pressure and temperature; the former steadily decreases (as does density) with increasing height as does temperature. At the tropopause, a variable layer from 35 to 55,000 ft., the temperature remains sensibly constant at about  $-56^{\circ}\text{C}$  until some 100,000 ft. when it begins to rise towards  $0^{\circ}\text{C}$  at the mesosphere at some 200,000 ft. Received solar radiation increases with height due to reduced atmospheric attenuation. Humidity decreases to a very low absolute water content. Wind, rain, hail, ice, fog and thunderstorms can all present specialist problems at altitude, problems which are largely extreme because of our limited knowledge of these environments. Corrosion, dust and sand and biological hazards do not really enter into altitude problems as such.

### **References**

- (1) SDM(L)89/3—War Dept. and M.O.A.—"Standardization Design Memorandum" No. 89, 1953.
- (2) "Human Engineering Guide to Equipment Design"—Morgan, Cook, Chapanis, Lund—McGraw Hill, 1963.
- (3) Av. P.35 "Environmental Handbook for G.W."—M.O.A., 1964.
- (4) "Handbook of Geophysics and Space Environments"—Air Force Cambridge Research Laboratories, 1965.
- (5) Av. P.35(4) Material, published and unpublished.
- (6) "Climate in Everyday Life"—Ernest Benn, London 1950.
- (7) "Handbook of Human Engineering Data for Design Engineers"—Tufts College, Mass.



*The Controller of the Navy, Vice Admiral Sir Horace Law accompanied by Captain A. Coleman, R.N., with Mr. R. W. Sutton and some of the Group Leaders, when he visited S.E.R.L. on December 14, 1967.*

# A SOLID STATE X-BAND RADAR BEACON

**H. L. H. Ward, R.N.S.S.**

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## Introduction

As part of the work on marine navigational aids which A.S.W.E. carries out on behalf of the Board of Trade, a solid state X-band radar beacon is being developed.

Radar transponder beacons or 'Racons' have a variety of possible marine applications, and are already used as an aid to navigation in identifying lighthouses and lightships. Existing designs of beacon use a klystron local oscillator and a magnetron transmitter, which delivers about 20W peak power output. In order to increase reliability and the possible applications a beacon is being developed which will use only solid-state components. At present the power output available in a suitable form from solid state sources will restrict the use of the beacon to short range applications such as marking harbour entrances where its small size and power requirements would enable it to be mounted on a light buoy.

## Specification

The specification for the existing magnetron beacon is as follows:—

### *Aerial*

Horizontal Beamwidth (for 2 dB maximum variation)	360°
Vertical 3 dB Beamwidth	27°
Gain	8 dB
VSWR	0·9

### *Receiver*

R.F. Bandwidth	150 Mc/s
Trigger Sensitivity	$3 \times 10^{-10}$ watts
Recovery Time	$45 \pm 2\mu$ secs.

### *Transmitter*

Tuning	Continuous
Tuning Range	9330-9480 Mc/s
Tuning Rate	2 Mc/s/sec.
Pulse Length	$45\mu$ sec.
Pulse Rise Time	$0.2\mu$ sec.
Peak Power Output	10 watts

The majority of marine radars have an aerial rotation rate of 24 RPM. The tuning rate of the beacon is 2 Mc/s/sec., so that the RF band is covered in 75 sec. This rate has been chosen so that the frequency lies within the 5 Mc/s minimum receiver bandwidth of the radar for a complete rotation of the aerial. The beacon signal therefore paints up at least once in every 75 secs.

The changes to be made in the specification for the solid state beacon will be in power output, pulse length and trigger sensitivity. The trigger sensitivity should be matched to the power output of the beacon, so that the beacon will not transmit when the response cannot be observed on the radar display.

### *Method of Operation*

The beacon frequency is swept continuously through 150 Mc/s by a 75 sec. duration sawtooth waveform. The transmission from the ship's radar is received by the omnidirectional beacon aerial, and is amplified in a crystal video receiver which uses integrated circuits (Fig. 1). The output from the receiver operates a P.I.N. diode switch to give a transmitted pulse of  $18\mu$  secs. ( $1\frac{1}{2}$  nautical miles), which is fed to the omnidirectional transmitting aerial. The beacon response appears on the radar P.P.I. as a radial line emanating from the true range of the beacon.

The double aerial system used at present will be replaced at a later date by a single aerial and a circulator.

### The Solid State Source

The beacon transmitter which was developed in A.S.W.E. consists of a C.W. operated solid state multiplier which delivers a minimum of 150 mW over the marine radar band from an input power of about 3 watts. Electronic tuning over the required band is achieved with a varactor diode in the oscillator circuit. The voltage tuning rate is about 30 Mc/s/volt and the characteristic is linear to about  $\pm 3$  Mc/s. The multiplier, using tightly coupled circuits, consists of an oscillator centred on 1175 Mc/s using an RCA.TA2710 followed by an RCA.TA7003 amplifier operating in Class C, a quadrupler stage using an H.P.0320 and a doubler with an unbiased H.P.0253. The output is in size 16 waveguide.

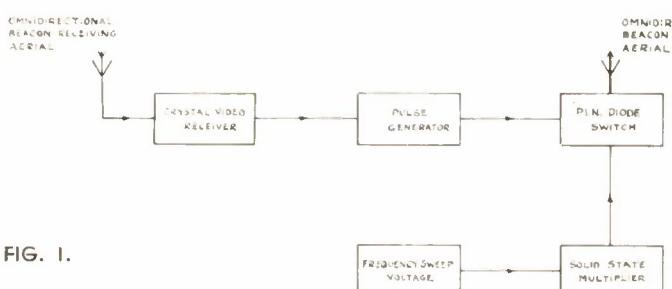


FIG. 1.

### Theoretical Performance

Consider the performance of a radar and beacon system having the following parameters:—

#### Beacon

Beacon Power

$$P_B = 150 \text{ mW}$$

Aerial Gain

$$G_B = 8 \text{ dB}$$

Trigger Signal at maximum Range

$$S_B$$

#### Radar

Peak Power

$$P_R = 10 \text{ kW}$$

Aerial Gain

$$G_R = 28 \text{ dB}$$

Aerial Rotation Rate

$$24 \text{ RPM}$$

Aerial Beamwidth

$$1.5^\circ$$

P.R.F.

$$1000/\text{sec.}$$

Noise Factor

$$N.F. = 12 \text{ dB}$$

Receiver Bandwidth

$$B = 5 \text{ Mc/s}$$

Wavelength

$$\lambda = 3.19 \text{ cm}$$

Minimum required signal power  $S_R$

These radar parameters are representative performance figures. It would be reasonable to add an additional overall system loss  $L_s = 3 \text{ dB}$ .

For a single pulse and 99.9% probability of detection with a  $10^{-5}$  false alarm probability the signal to noise ( $S/N$ ) ratio is 15 dB<sup>(1)</sup>. The number of pulses per beamwidth

$$= \frac{1.5}{360} \times \frac{60}{24} \times 1000 = 10.$$

This should reduce the required  $S/N$  ratio by  $\sqrt{10}$  or 5 dB. However, due to the beam shape and only partial overlapping of the pulses an improvement of 3 dB is assumed, making the required  $S/N$  ratio = 12 dB.

$$\text{Then } S_R = S/N + N.F. + kTB$$

$$= 12 + 12 + 10 \log_{10} (4 \times 10^{-21} \times 5 \times 10^6) \\ = 12 + 12 + 3 - 140$$

$$\therefore S_R = -113 \text{ dBW}$$

The free space range from the beacon to the radar is given by

$$R_B = \sqrt{\frac{P_B G_B G_R \lambda^2}{16\pi^2 L_s S_R}}$$

$$\text{Whence } R_B = 10.5 \text{ miles}$$

In very heavy rain of about 16 mm/hr. the one way attenuation is  $3 \times 10^{-1}$  dB/km<sup>(2)</sup>, and the range would be reduced to about six miles.

The range from the radar to the beacon will be given by

$$R_R = \sqrt{\frac{P_R G_R G_B \lambda^2}{16\pi^2 L_s S_B}}$$

At a range of 10.5 miles

$$S_B = -35 \text{ dBm}$$

So that the full sensitivity available from a crystal-video receiver will not be required.

### Preliminary Measurements of Performance

Some preliminary measurements were made over a sea path using a 10 mW beacon transmitter. The range for an approximate 50% probability of detection was 3.5 miles. Adjusting for the different probability of detection and radar parameters previously referred to, the corresponding range is 3 miles. Thus these measurements indicate a potential range of  $3\sqrt{15} = 11.5$  miles for a 150 mW source.

Measurements were made overland at a range of 5 miles, using the 150 mW transmitter. The beacon response was just discernible on the radar P.P.I. with an attenuation of 9 dB in the output of the beacon. This indicates a useful range of about 12 miles.

### References

<sup>(1)</sup> Introduction to Radar Systems. Skolnik. McGraw Hill Book Co. p.34.

<sup>(2)</sup> Ibid. p.544.

# PERMANENT INTERNATIONAL COMMITTEE FOR RESEARCH ON THE PRESERVATION OF MATERIALS IN THE MARINE ENVIRONMENT

**Reported by D. R. Houghton, B.Sc., M.I.Biol., R.N.S.S.**  
*Central Dockyard Laboratory*

A meeting of the General Assembly of the above mentioned committee took place on the 5th and 6th October 1967, preceded by the meetings of the three sub-groups.

The election of the executive committee was deferred until the next meeting in order to allow representatives from Germany and the United States to be present.

A few small modifications were made to the "rules of procedure" and applications for membership from organizations in Yugoslavia and Sweden were discussed. It was decided that further information should be sought concerning these applicants. Israel had shown interest in the committee and it was suggested that the British Iron and Steel Research Association and the British Ship Research Association be invited to join.

The assembly approved the setting up of a sub-group to study the problems of corrosion and fouling on offshore installations.

Discussions took place on the possibilities of undertaking work on organic copper and lead toxins, the inclusion of toxins in plastics, prevention of fouling by use of ultra-sonics and radioactive methods. It was decided that each proposer should review the present state of knowledge in these fields and submit their proposals to the next meeting of the General Assembly.

The possibilities of issuing an information bulletin were discussed and the suggestion approved in principle. Financing of further volumes of the Catalogue on the Main Marine Fouling Organisms was reviewed and it was decided that U.N.E.S.C.O. might be approached in this connection.

The data on the preparation and protection of ships' plate in the shipyards of member countries would be brought up to date and published in about two years time.

## Sub Group on Biology

In the past data collected from the testing stations had been very difficult to correlate because of the different methods employed in the study of

hydrology and fouling. It was, therefore, proposed that standard methods be adopted and a paper was circulated laying down procedures for

- (a) Settlement of fouling organisms
- (b) Recording of sea and air temperatures
- (c) Recording number of hours of sunshine
- (d) Estimation of dissolved oxygen content of seawater
- (e) Determination of salinity
- (f) Measurement of the velocity of the tidal stream
- (g) Light penetration.

It was agreed that written comments on the proposals would be sent in by the delegates; these would be included in a re-write of the document and sent to delegates prior to the next meeting.

A proposal to study the antifouling properties of copper alloys was deferred until the next meeting so that delegates could review the work already carried out. They would then send in their comments which would be circulated to delegates before the next meeting.

## Sub Group on Leaching Rates of Antifouling Paints

A report on the work carried out in the U.K., Netherlands, Denmark and Italy using a standard method was reviewed. There were considerable differences in results in some cases. The sub group agreed that a close study of the factors involved such as hydrological conditions, thickness of paint film etc. should be made to try and elucidate the causes of the differences.

It was hoped that a new series of experiments could be started in 1968.

## Sub Group on Underwater Protective Coatings

Discussions took place on the finalization of the programme of underwater protective coatings to be studied under raft and laboratory conditions using cathodic protection. Agreement was reached after a few minor additions and the starting date fixed for 15th January 1968.

# GAS-JET LASER CUTTING

**A. B. J. Sullivan, R.N.S.S.**

*Services Electronics Research Laboratory  
and*

**P. T. Houldcroft**

*British Welding Research Association*

*A new technique for oxygen cutting metals has been developed which employs a laser beam for preheating. Fine cuts with negligible heat-affected zones have been made in sheet steel. The process appears to be capable of development for cutting thicker metal as well as a variety of metals and non-metals.*

## Introduction

The discovery of the carbon dioxide laser system now capable of outputs of up to a kilowatt and an efficiency of 20% has provided a new heat source of potential value in welding and cutting. This laser generates radiation at a wavelength of  $10\mu$  and has the coherent light properties common to all gas lasers<sup>(1)</sup>.

Until recently lasers capable of melting and cutting metal were of the solid-state type, with an intermittent output so that only discrete melted spots could be made. An important characteristic of the carbon dioxide laser is that the output is continuous, allowing an uninterrupted weld seam or cut to be made.

In previous reported work on laser cutting the mechanism of cutting has involved bringing a laser beam to a focus on the workpiece so that the energy density is sufficient to first melt and then boil and vaporise metal from the area to be cut<sup>(2)</sup>. With a laser output of 300 W as used in the present work, the best focus achieved has been about 0·009 in. diameter and more usually 0·016 in. diameter. The output power density for 0·016 diameter focus is approximately 250 kW/cm<sup>2</sup> which will boil metal or ceramic readily. Using this laser, cuts have been made in steel sheet of 0·010 in. thickness.

With a given laser radiation density, the temperature attained at a metal surface depends on the rate of movement of the metal, its heat flow properties and reflectivity. Reflectivity changes with oxidation or other chemical changes at the surface, a metal whose reflectivity decreases with oxidation heating more readily.

The heat generated varies from metal to metal. Tungsten and molybdenum having high reflectivity and good thermal conductivity are difficult to heat. The same is true of aluminium which although it has a low melting point, has a high thermal conductivity and specific heat as well as good reflectivity. Stainless steel and the steel alloys on the other hand, although having a bright surface, readily heat because they have relatively poor thermal conductivity. These considerations apply equally to cutting or welding by the laser.

## Gas-jet Laser Cutting

Conventional cutting techniques such as plasma arc or oxy-acetylene employ melting and erosion in a high velocity gas stream or utilise the exothermic reaction between iron and oxygen to assist the process. The width of the kerf is largely determined by the diameter and characteristics of the gas stream and is normally over 0·050 in. and frequently 0·10 in.

The new process depends on the discovery that when an oxygen jet in combination with a laser beam is used for cutting, the width of the kerf is determined not by the diameter of the gas jet but by the size of the focused laser spot. Once the laser beam has raised the metal to a high temperature the oxygen reaction begins, providing additional heat and forming fluid oxides of the metal which are then expelled from the kerf by the action of the jet. The result is that substantially thicker metal may be cut than with the laser alone with a relatively small increase in the width of the cut.

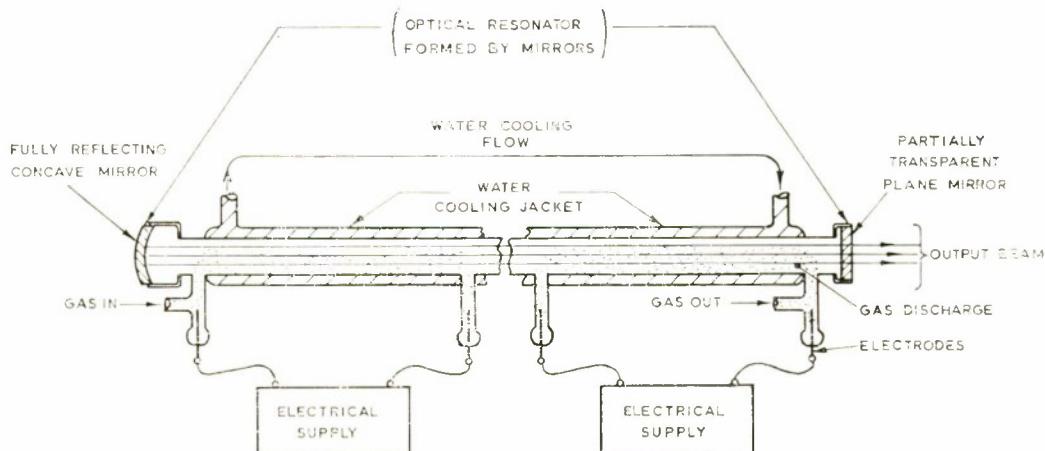


FIG. 1. Outline diagram of a carbon dioxide laser.

## Equipment

The apparatus for the new technique comprises the laser, optical system and a chamber which permits the oxygen jet and laser beam to emerge co-axially.

The laser used was of the carbon dioxide-nitrogen-helium type with a total length of 10 metres and a 30 mm bore. There are five sections to the tube, each section having its own electrodes and power supply providing 20 kV for striking and 9 kV at 45 mA when the laser is running. A general arrangement of the laser is shown in Fig. 1 where only two sections are indicated. The cavity has a gold surfaced stainless steel mirror of 10 metre focal length at one end and a plane semi-reflecting germanium disc at the other. It is through this disc that the laser beam emerges with a diameter of 0.75 in. and an output power of 300 W. The present laser is operated from an a.c. supply for simplicity so the output follows the mains frequency of the input, which at 50 Hz gives a pulsed output of 100 pulses per second (p.p.s.).

Fig. 2 shows how the beam is deflected downwards by means of a front aluminized mirror, through a focusing lens and into the oxygen chamber via a plane transparent window fitted at one end. The other end of the chamber has a nozzle permitting an oxygen jet to be directed at the metal surface. The laser beam is brought to a focus down the centre of the jet and emerges co-axially with the oxygen stream to be focused about  $\frac{1}{16}$  in. outside the nozzle exit. The position of this focal point can be adjusted and the nozzle changed according to requirements. A focal position  $\frac{1}{16}$  in. beyond the nozzle has been found optimum when using a 0.10 in. diameter oxygen jet and gives a clean and stable cut. When other jet sizes are used the focal point takes a similar position in proportion to the nozzle diameter.

The metal to be cut is placed horizontally below the oxygen jet at the focus of the laser beam, and can be moved horizontally to allow the cut to progress. The accurate positioning of the work face at the focus is essential in the present arrangement but is not fundamental. A suitable lens system could be devised to produce a parallel beam of small diameter allowing reasonable latitude in positioning the work or adjustment of the oxygen jet.

## Results

Cuts of up to 0.020 in. kerf width with both straight and shaped outline have been made in mild steel, high carbon tool steel and stainless steel of 0.10 in. thickness at speeds up to 40 in./min. Generally the kerf width is wider than the laser focus

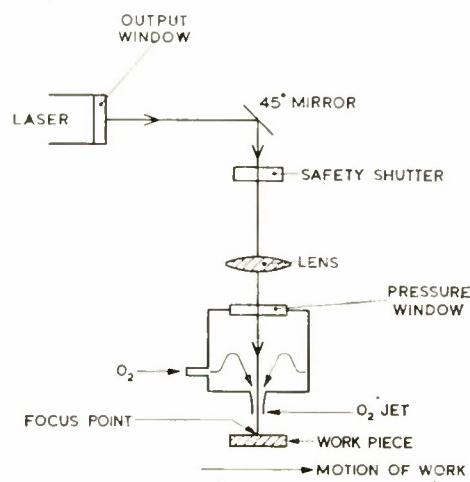


FIG. 2. General arrangement for gas-jet laser cutting, showing optical system and oxygen chamber.

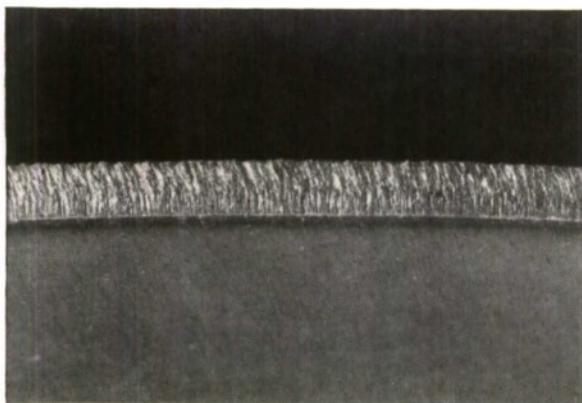


FIG. 3. Cut edge of cut in 0·080 in. thick high carbon steel made at 40 in./min.

by about one-third, *i.e.* a focus dia. of 0·012 in. will give a kerf width of 0·016 in. In terms of thickness of metal cut the oxygen assisted cutting process gives an advance of approximately an order of magnitude over what can be achieved with the unaided laser. The narrowness of cut promises a precision not previously obtained with oxy-acetylene cutting techniques.

The cut edge, shown in Fig. 3, indicates how the process proceeds intermittently, following the 100 p.p.s. output of the laser. A maximum speed of cut of about 40 in./min. has been achieved with a focus of approximately 0·012 in. Provision of greater power would enable a higher speed to be achieved, but with the laser operating at effectively 100 p.p.s. difficulty would probably be encountered because the heat zones would become separated. At the speeds mentioned the heat zones are spaced at approximately 0·007 in. intervals and with a spot size of 0·012-0·020 in. there is sufficient overlap. However, by operating the laser from a d.c. source, higher power would enable cutting speeds to be increased.

The smoothness and stability of the process is also dependent upon exceeding a minimum speed of approximately 8 in./min. Below this speed the oxygen-steel reaction propagates beyond the laser heated area to the limits of the oxygen boundary. This results in large holes being melted and intermittent operation of the cutting process. As the cutting speed is increased the reaction is inhibited from spreading sideways because the steel is moved out of the oxygen stream before this can occur.

Fig. 4, a photomicrograph through the cut edge of a high carbon tool steel, clearly shows the narrow heat-affected zone and the ripple effect due to the 100 Hz pulsing. The heat-affected zone which

has etched light, is 0·003 in. thick and is entirely free from the cracks or hot tears which might have been expected with other less rapid methods of heating.

### Future Development

Only a limited amount of work has been done on gas-jet laser cutting so far. The system shows promise of providing a precision cutting method for thin materials. There is negligible distortion and heat affected zone. Although most of the work has been done on ferrous metals, it is believed that this process should be effective on other materials less easy to machine. There are no mechanical forces to react in gas-jet laser cutting which could be an advantage if cuts must be made in thin or delicate parts.

With the development of lasers of higher power it may be possible to cut considerably greater thicknesses than those reported. This expectation is justified by the fact that in oxy-acetylene cutting the rate at which the top surface can be preheated to reaction temperature is a critical parameter of the cutting process.

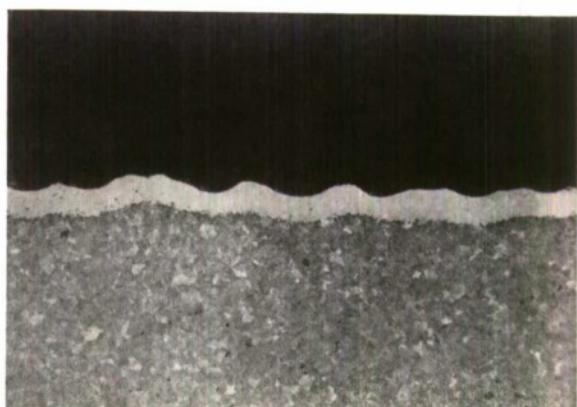


FIG. 4. Photomicrograph of etched section of a cut edge from sample shown in Fig. 3. x 50.

The process may be extended to other gases than oxygen and a range of metals and non-metals if an exothermic reaction with or without the production of volatile compounds can be achieved.

### References

- (1) C. K. N. Patel, P. K. Tien and J. H. McFee. *Applied Phys. Letters*, **7** (1965), 290.
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## Retirements

### J. HEWITT, R.N.S.S.

Joining the Admiralty as an apprentice 53 years ago, Jack Hewitt has spent 46 of them in what is now the R.N.S.S. This would seem to be an all-time record.

He joined the Signal School in 1921 as an Electrical Fitter on Drawing Duties and was confirmed as a draughtsman in 1925, working on communication equipment for both Ships and Shore Stations. In June 1938 he was promoted to an Assistant Grade II in the Production Department under Mr. Peake and the present Director of Production, Mr. Birkett. Like many others he was evacuated to A.S.E. Haslemere in 1941 where he helped to train new entrants into Service methods. In 1943 he rejoined the Design Division and worked under Mr. Bishop on the mechanical design aspects of radars such as 275, 277. After the war, in 1946, he was appointed an Experimental Officer in the R.N.S.S. and worked with Mr. Moss (CX) on VHF and UHF development, and was promoted to S.E.O. in July 1948.



In 1954 he followed Mr. Birkett as Officer-in-Charge Workshops and in 1956 was appointed a Chief Experimental Officer when he took over the title of Works Manager. He remained in this post to his 60th birthday and during his time as Works Manager the workshops produced many parts of major projects including the aerials for *Spatula* and Type 965. Since 1959 he has been dis-established and has continued to serve, up to the present day, as an Experimental Officer on the post design aspects of Shore Station equipments.

Hewitt's hobby up to 1938 was the Territorial Army and he served for 16 years in the Hampshire Heavy Brigade R.A. (T.A.) and this experience led to his work in the A.S.E. Battalion of the Surrey Home Guard at Lythe Hill in which he was the Regimental Sergeant Major. Later at the request of Captain Willett, he trained a squad of A.S.E. Wrens for the Southern Command W.R.N.S. Foot Drill and Marching Competition held at Lancing College, and brought them home second to the Whale Island team.

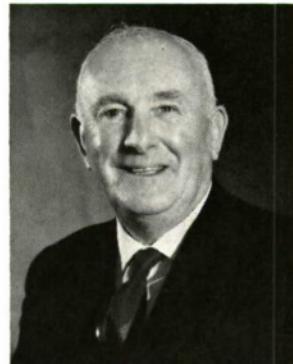
He is a Hi-Fi enthusiast and a member of the Music Section of the Sports Club, and for many years he has been President of the A.S.W.E. Workshops Cricket Club. He is entitled to wear the King George VI Coron-

ation Medal which was presented to him by the then Captain Superintendent of A.S.R.E., Captain W. J. Lamb, R.N.



### F. L. HILL, R.N.S.S.

Frank Leslie Hill retired on 30th November, 1967, after 43 years' service. He began his Admiralty career when he joined the Scientific Section of Mine Design Department, H.M.S. *Vernon*, in 1924 and remained with M.D.D. on its removal to the Grammar School, Portsmouth, and later in 1940 to West Leigh House near Havant. During these years he was concerned with a variety of materials problems associated with new mines and did much of the laboratory work required to develop mu-metal rods and wires for the A.E. and C.R. Units which found extensive application in magnetic mines and detection magnetometers during the war.



Later, he turned his attention to naval applications of electro-chemistry, and contributed towards the development of the antenna mine, the Staybrite sweep and jumping wires as net indicators on submarines, and also electrolytic and other timing devices which were needed to replace clocks which were in very short supply during a critical period of the war. He was promoted to Senior Experimental Officer on 1st July, 1947.

In 1950 he joined the Central Metallurgical Laboratory at Emsworth to work on the application of hot plastic antifouling compositions. When C.M.L. was closed down in 1956 he joined the Admiralty Materials Laboratory where his previous experience at M.D.D. was immediately helpful in connection with a mine-coating project. On completion of this work he became interested in the erosion of materials in high speed seawater environments. His work in this field produced much of the information on which materials were selected for the new design of assault ships.

Throughout his career Hill was always ready to draw on his long experience to give help and advice to younger colleagues, many of whom will remember him with gratitude for his guidance in getting them quickly conditioned to the Service environment.

On behalf of his colleagues Dr. T. C. J. Ovenston presented Mr. Hill with an elegant mantel clock, with their best wishes for many happy years of retirement.



**L. KENWORTHY, M.Sc.,  
F.R.I.C., F.I.C.T., R.N.S.S.**

Leslie Kenworthy retired on 31st January, 1968, after 38 years' service, first with the British Non-Ferrous Metals Research Association and later with the Admiralty. He was educated at the City of Norwich School and Imperial College and, after graduating in 1929, he joined the B.N.F.M.R.A., initially working in Birmingham University and later in London when the Association opened their own laboratories. He was first employed in investigating the corrosion of tin and its alloys, and this proved to be the beginning of a specialization in the subject of metallic corrosion which he followed for the whole of his career. Whilst at the B.N.F.M.R.A. he also carried out researches on the reflectivity of highly polished metals, the surface finish of rolled brass and copper, corrosion in domestic water systems, condenser tube corrosion, zinc coatings and the galvanizing process. He was awarded a London External M.Sc. degree in 1932.



In 1941, he was seconded to the Admiralty, joining the staff of the Central Metallurgical Laboratory, Emsworth. At this time our ships were being immobilized by corrosion in the seawater cooling systems brought about by the strenuous conditions of war-time operation. The investigation of this problem was Kenworthy's main task in the war years, and involved him in the inspection of all the major units of the Fleet, as well as a high proportion of all other ships, many on several occasions. The outcome of this work was a B.R. on the Prevention of Corrosion in Sea Water Cooling Systems.

Having decided not to return to the B.N.F.M.R.A., he was assimilated as a Principal Scientific Officer in 1947. In that year he was appointed Secretary of the Admiralty Corrosion Committee, a post which he held

up to his retirement, and it is the work he carried out in connection with the activities of this Committee (now known as the Navy Department Committee for the Prevention of Corrosion and Fouling) for which he will probably be best remembered in the Navy Department.

In 1949 he became Officer-in-Charge of the Central Metallurgical Laboratory which had grown from a small dockyard laboratory in Portsmouth in the 1930s, to employ over 100 staff, including its out-station laboratories in Portsmouth, Chatham, Devonport, Rosyth and Malta Yards and at the R.N. Torpedo Factory, Greenock. In his charge, the laboratory came to devote more effort to long term investigations on corrosion and marine fouling; re-circulating seawater systems in conjunction with the Yarrow Admiralty Research Department were set up, and extensive testing facilities in Chichester Harbour for seawater immersion and half tide and aerial exposure were established.

In 1956, in accordance with a policy of amalgamating some of the smaller establishments, C.M.L. was closed and Kenworthy was appointed to the Admiralty Materials Laboratory where he concentrated on the work of the Corrosion Committee which had been expanding considerably, especially as regards liaison with the Commonwealth Navies. This involved him to an increasing extent in work of an advisory nature and with membership of numerous Service, Inter-Service, National and International Committees on corrosion and its prevention. He served as Chairman of many of these, including the Scientific Committee of the 1st International Congress on Metallic Corrosion held in 1961 under the auspices of the International Union for Pure and Applied Chemistry, the Corrosion Group of the Society of Chemical Industry from 1959 to 1961, and the Main Corrosion Committee of the British Iron and Steel Research Association from 1961 to 1967. He lectured widely, and gave the Annual Lecture to the Australasian Corrosion Association in 1965. Recently he was made an honorary life Fellow of the Institute of Corrosion Technology.

In addition to these various activities, he headed the small but effective Applied Biology Division at A.M.L. The work of this group was started at Emsworth and has been further developed at A.M.L., mainly for the diagnosis and control of biological attack on materials and equipment in Service use.

To mark the occasion of his retirement he was presented with a portable typewriter by Dr. T. C. J. Ovenson on behalf of his colleagues in the Department of Materials Research (Naval), the Central Dockyard Laboratory, Portsmouth, and A.M.L.



**H. J. TAYLOR,  
B.Sc., Ph.D., R.N.S.S.**

Dr. H. J. Taylor relinquished his post at the Royal Naval Physiological Laboratory, Alverstoke early in October, 1967, after being Superintendent for over 20 years. Before joining the Government Service in 1944 he worked for many years with Professor Sir Leonard Hill, F.R.S., one of the pioneers of pressure research and later at the National Institute for Medical Research with Dr. Argyll Campbell, developing a method for measuring oxygen tension in tissue. On joining the R.N.P.L. he applied these methods to investigate CO<sub>2</sub> and O<sub>2</sub> tensions in the tissues of animals under raised oxygen pressures. He also demonstrated that by intermittent exposure of animals to oxygen they could become "acclimatized". With Dr. C. L. G. Pratt he then started work on Submarine Escape as a result of a review by the Ruck Keene Committee (of which he was a member). This led to the method, now universally adopted, of so-called free ascent. Experiments on animals were subsequently confirmed on man and Dr. H. J. Taylor and a colleague Dr. H. C. Wright were the first to test out the rapid ascent method together at various depths. The Training Tank at *Dolphin* was built as a result of this fundamental research work. All subsequent work, leading to human escapes from what were considered to be of impossible depths, stems from this original work.

In collaboration with Dr. W. W. Davidson (now Surgeon Captain) he commenced research work on Decompression Procedures, and so far as is known, the first information regarding tissue saturation times was obtained. One can say that under Dr. Taylor the laboratory has acquired a world-wide reputation.

On being appointed Acting Superintendent in 1947, and confirmed early in 1948, one of Dr. Taylor's chief concerns was the poor accommodation for his Staff working in the laboratory. Functionally, the laboratory was a series of decrepit wooden huts with an ancient cottage and one pre-fabricated building used as a laboratory and workshop.

However, in 1962, as a result of continued pressure, R.N.P.L. was allocated new premises at Fort Road, Alverstoke. This site was formerly an accommodation centre for naval personnel, and comprised a collection of buildings, all of which had to be adapted to the needs of the laboratory. It was mainly due to Dr. Taylor's efforts, together with the closest co-operation of all the Staff, that some semblance of a suitable laboratory was established. In recent years, the facilities for research into the problems of deep diving have been expanded with the installation of a three compartment 800 ft. pressure chamber, and a two compartment pressure chamber capable of simulating 'dry' dives to 2,250 ft.

A close liaison with the Admiralty Experimental Diving Unit has also been maintained, culminating in the building in the grounds of R.N.P.L. of a new research facility known as the Deep Trials Unit, in which experiments to depths of over 1,000 ft. can be carried out under 'dry' or 'wet' conditions. The equipment for pressure work at R.N.P.L. is therefore, not only unique in this country, but the envy of other nations.

Dr. Taylor has been a member of both the Physiological Society and of the Ergonomics Research Society of which he is a founder member. In his Scientific career he has published well over 50 papers and some of these have been included in the Proceedings of the Royal Society.



His outside activities are numerous. He is a Councillor for the Alverstoke Ward on the Gosport Borough Council and a member of many Committees of that Council, a Governor of several schools of the Gosport Education Committee and a Governor of Highbury Technical College of the Portsmouth Education Committee. He is a member of the advisory board for Science and Mathematics of the latter college. He and his wife have always been keen collectors of porcelain, glass and silver and are members of many societies dealing with these objects. Their collection has to be seen to be believed.

Dr. and Mrs. Taylor have a fairly large and expanding number of grandchildren and one of the pleasures of retirement will be that he will be able to spend more time with them.



## C. D. LAWRENCE, O.B.E., Ph.D., D.I.C., B.Sc., F.R.I.C., R.N.S.S.

Cyril D. Lawrence, who retired on 31st March, spent the whole of his 34 years Admiralty servicee in the sphere of chemistry, first at N.O.I.L., Holton Heath and then at the Central Dockyard Laboratory, Portsmouth. After four years at Cardiff High School, he made an early plunge into the industrial environment as Assistant Chemist in the Lewis Merthyr Consolidated Collieries. Armed with three years experience of the outside world,



he then pursued his academic studies firstly at the South Wales School of Mines and subsequently at Imperial College, London. During his period of research work at the latter he was a Royal Scholar during 1926-28 and in the subsequent year was Research Assistant to Professor Bone, F.R.S.

His Service career commenced in 1929 when he was appointed to the N.O.I. Laboratory at Holton Heath. In 1931 he moved to Portsmouth, to the then Admiralty Chemist's Department, and he was to remain here for the rest of his career, apart from a year back at Holton

Heath in 1939 during a period of re-arrangement. He was promoted Chemist in 1935, and Senior Chemist in 1940; in 1944 he succeeded F. H. Newington as Head of the Laboratory with the rank of Principal Chemist, and in 1946 assumed the present title of Superintending Scientist with the rank of S.P.S.O.

In 1956 the title of the Laboratory was changed to Central Dockyard Laboratory, since by now it had acquired outstation laboratories at Devonport, Chatham and Rosyth. The administration, and integration of these Dockyard Laboratories with the Central Laboratory was a task to which Dr. Lawrence devoted great attention, and the smooth working of the organization and the valuable part which each laboratory is able to play in its local sphere owe much to his skilful guidance.

During the past decade Dr. Lawrence has been the Chairman of the Main and Underwater Sub-committee of the Navy Department Committee on the Prevention of Fouling and Corrosion and his activities also extended into Europe under the aegis of the O.E.E.C. Group of Experts on the Corrosion and Fouling of Ships' Hulls. In 1959 he was host to the Plenary Session of this body which met at Portsmouth, and was appointed Chairman of the Commission concerned with Fundamental Research. He was elected Chairman of the Research Group on Underwater Protective Coatings in 1964, and subsequently played an important rôle in setting up the Permanent International Committee for Research on the Preservation of Materials in the Marine Environment, which succeeded the Group outside O.E.C.D. in 1967.

The award of the O.B.E., in 1958, was a source of gratification to his colleagues and friends, who will now wish him well in his retirement in his delightful new home on the Isle of Wight, which overlooks the Solent from an idyllic position on the waterfront.



**R. W. SUTTON,**  
**C.B., O.B.E., B.Sc., R.N.S.S.**



Robert Sutton retired from the post of Superintendent of the Services Electronics Research Laboratory on February 2nd, 1968—he had been the Superintendent of S.E.R.L. since its foundation in 1945.

Having spent about 10 years in Industry, Mr. Sutton joined the Admiralty in 1939 as the youngest Senior Scientific Officer at H.M. Signal School at Portsmouth. Both at Ferranti and E. K. Cole he had been engaged in valve development and, with the imminence of war, he was asked to join the Service to build up a team to do research and development on special valves for the rapidly expanding radar programme. This work was immediately concentrated on the then entirely new field of microwaves.

After the fall of France in 1940 the group was transferred to Bristol University and during the time there the now well-known work on microwave oscillators for the first naval and airborne microwave systems was rapidly progressed, as also was the development of the skiatron or darktrace cathode ray tube for radar displays.

Early in 1945 proposals were being made to set up an Inter-Service R and D Establishment in the field of active electronic devices and Mr. Sutton had the task of establishing and building up what was to become known as the Services Electronics Research Laboratory. This Laboratory, which was housed in a war-time shadow factory at Baldock, was originally staffed by the amalgamation of various Admiralty teams which had been working in the electronics devices field—par-

ticularly those of the Admiralty Signal Establishment Extensions at Bristol and Waterlooville. Mr. Sutton was appointed the first Superintendent of S.E.R.L. and has remained in that office until his retirement.

S.E.R.L., which forms the intra-mural activity of the Inter-Services Co-ordination of Valve Development organization, has made many notable contributions in research and technology during the last 22 years. Developments include a large number of new high power microwave tubes such as magnetrons and travelling wave tubes for radar, communications and electronic warfare, and low power tubes for microwave receivers. The Laboratory has pioneered many aspects of the newer field of semiconductor devices—in particular those using the compound semiconductors such as gallium arsenide, indium antimonide and gallium phosphide. These include microwave solid state devices and solid state generators and detectors of visible and infra-red light.

An outstanding achievement with which Mr. Sutton has been particularly associated was the development of a compact, sealed-off, neutron source (known to many at S.E.R.L. as "The Thing") for atomic weapon initiation. Further developments of this device have provided sources for civil applications and these in common with many other S.E.R.L. developments are now in production in Industry.

Mr. Sutton is now returning to the electronics industry and his many colleagues offer him their very best wishes for the future.



## J. H. OLDFIELD, F.R.I.C., R.N.S.S.

Joseph Howard Oldfield retired on 15th December, 1967, after 41 years of service. He was born and educated in Sheffield and took his first job there as a Laboratory Assistant with Steel, Peach & Tozer Ltd. In 1926 he joined the Admiralty at what was to become the Bragg Laboratory and gained a thorough knowledge of the classical approach to metallurgical analysis.

He first became interested in the spectrograph in 1937, when the laboratory acquired its first instrument, and this set the pattern for his subsequent career. With Barker and Hornby he pioneered the application of this technique to the analysis of steels. The war years were spent at an out-station at Sheffield University where, amongst other things, he developed a microspark traversing technique for detecting heterogeneity in steel.

He quickly came to realize the potential value of direct reading emission spectrography and was successful in adapting a photographic instrument for direct reading at a time when the increased volume of work occasioned by the Korean war strained existing practices.



He joined the Admiralty Materials Laboratory in 1955 at a time when developing semi-conductor technology was demanding analytical sensitivity in advance of anything previously experienced. He met this challenge by further successful exploitation of the spectrograph, by developing a new technique which became known to spectrographers as "The Oldfield Method".

In 1947 he was promoted to Senior Experimental Officer and was then awarded the Associateship of the Royal Institute of Chemistry, gaining full Fellowship only three years later, in recognition of his contributions to emission spectrography. For many years he was Chairman, both of the B.I.S.R.A. Spectrographic Sub-Committee and of the Inter-Services Spectrograph Panel.

Oldfield is a keen and active amateur photographer, and twice served as Chairman of the A.M.L. Photographic Society. On behalf of his colleagues Dr. T. C. J. Ovenson presented him with a parallax adjuster for his twin-lens reflex camera and a framed reproduction of a well-known Canaletto.

## Notes and News

### Admiralty Materials Laboratory

Mr. L. Kenworthy visited The Hague on October 27th to give a lecture on "Some Corrosion and Deterioration Problems met with in Naval Ships and Equipment" to the Dutch Institute of Marine Engineers.

Mr. N. I. Hendy travelled to the U.S. during November, 1967 where he attended the 16th Conference on Prevention of Microbiological Deterioration at the U.S. Army Natick Laboratories, and visited Florida State University, University of Rhode Island and the Smithsonian Institute, for discussions on oil pollution and coastal waters.

Mr. D. H. Fanner also visited the U.S. during November, 1967 to discuss a Memorandum of Understanding on the exchange of information on Fuel Cell Research, and to visit U.S. Army and Navy Establishments and Contractors concerned with Fuel Cell development.

The following papers have been published by members of the staff:—

"Statistical and Practical Approaches to the Development of Design Criteria for Brittle Materials" by D. J. Godfrey and K. W. Mitchell, *The Engineer*, 224 (1967) 737. "Excited Complex formed by Mixed Triplet Interaction" by C. A. Parker and T. A. Joyce, *Chem. Commun.* (1967) 1138 and "Electrochemiluminescence of 9, 10-Dimethylanthracene in Dimethylformamide" by C. A. Parker and G. D. Short, *Trans, Faraday Soc.*, 63 (1967) 2618.



### Services Electronics Research Laboratory

Dr. M. O. Bryant visited the U.S.A. during the period 5th-21st October to attend the I.E.E.E. International Electron Devices Meeting in Washington, D.C., and to make visits to laboratories working in the fields of high power microwave valves and solid state devices. At the I.E.E.E. conference, he presented a paper entitled "Advances in High Power c.w. Travelling-wave Tubes" co-authored by Messrs. L. D. Clough and F. E. Wray.

The Secretary of State for Defence, the Rt. Hon. Denis Healey, visited S.E.R.L. on Monday, 13th November, 1967 and toured the Laboratory. He was accompanied by his Private Secretary, Mr. E. Broadbent, and Mr. A. W. Ross, D.N.P.R.



*The Minister of Defence with the Superintendent of S.E.R.L. examining a new design of high power travelling wave tube during his visit on 13th November, 1967.*

A party of the Cambridge Archimedean Society visited S.E.R.L. on the 1st December. The Society consists of undergraduate mathematicians. The party toured the Laboratory and saw demonstrations of an argon laser, holograph, a ring laser, molecular gas lasers, ion implantation, neutron tubes and applications, new semiconductor materials, gallium phosphide lamps and a gallium arsenide laser. The visit concluded with tea, when the visitors were able to continue their discussions with the demonstrators. The Archimedians have stated that it was useful to be able to talk about the work and opportunities at Baldoek. Perhaps we can hope the exercise may have had an anti-brain-draining effect.

Mr. C. H. Gooch recently visited the U.S.A. to attend the I.E.E.E. Semiconductor Laser Conference which was held at Las Vegas. At this conference he presented a paper entitled "The Thermal Properties of Gallium Arsenide Lasers".

A B.B.C. TV camera team has again visited the Laboratory, on this occasion to photograph a demonstration of metal cutting by means of the focused beam of a carbon dioxide laser. The film was shown in *Tomorrow's World* as part of a programme on the applications of lasers.

Mr. P. Gurnell and Mr. B. R. Holeman paid a visit to France on 4th and 5th January under Anglo-French Collaboration, to visit firms in connection with Indium Antimonide Photo-voltaic Detectors.

Mr. J. W. Allen and Mr. D. R. Wight attended a conference on Solid State Physics at Manchester University in January, and Mr. Allen read a paper entitled "Energy Levels of Iso-electronic Impurities". Travelling back on January 6th they were involved in the train accident at Hixon, and were lucky to escape with minor cuts and bruises.

Mr. H. Foster and Mr. J. Beesley attended a Conference on "Holography—Recent Advances and Applications", at N.P.L. Teddington on 17th-18th January, 1968.

On retirement from S.E.R.L., the Superintendent, Mr. R. W. Sutton, was presented by the staff with an engraved silver tray and an album of photographs illustrating the many technical achievements of the Laboratory under his direction. Mrs. Sutton, who attended the ceremony, received a bouquet. The presentation was made by Mr. D. W. Downton on behalf of the staff representatives' committee. Mr. Sutton responded by presenting a silver trophy to the S.E.R.L. Sports Club.

## Book Reviews

**Metals Reference Book.** By C. J. Smithells. Pp. xiv + 1147. London; Butterworth & Co. (Publishers) Ltd., 1967. Price 315s. 3 Vols.

This standard reference work has for nearly twenty years provided a convenient summary of data relating to metallurgy and metal physics. Its soundness and dependability have been proved by the fact that it now appears in its Fourth Edition, revised and expanded to bring it completely up to date.

Throughout the volumes the data are logically presented in the form of tables and diagrams, with the minimum of descriptive matter. Short monographs are included where information could not be clearly presented. A short bibliography at the end of each chapter enables the reader to refer to important original sources.

Volume I includes introductory tables. General physical and chemical constants. Line spectra of the elements. X-ray crystallography. Crystallography. Crystal chemistry. Geochemistry. Thermochemical data. Physical properties of molten salts. Metallography.

Volume II—Equilibrium diagrams. Gas-Metal systems. Diffusion in metals.

Volume III—General physical properties. Elastic and damping capacity thermoelectric properties and temperature measurement. Radiating properties of metals. Thermionics, photoelectric and secondary emission. Electrical properties. Steels and alloys with special magnetic properties. Mechanical testing. Mechanical properties of metals and alloys. Hard metals. Deep drawing properties. Lubricants. Friction. Casting alloys and foundry data. Refractory materials. Fuels. Carbon and graphite electrodes. Controlled atmospheres for heat-treatment. Masers and lasers.

Corrosion resistance of metals. Electroplating and metal finishing. Welding. Solders and brazing alloys. Miscellaneous data. Index.

Over 300 pages of Volume I are devoted to data on mathematical formulae, line spectra, crystallography, crystal chemistry and thermochemistry. The values given, are those to which contributors have selected as the most reliable after a critical review of published data. It is believed that the contributors' choice is likely to be more reliable than that which the reader might make from a series of conflicting values, especially if he is not a specialist in the field in question. The latter section on metallography describes techniques for the examination of metals for structural and surface features at all magnifications.

Volume II contains over 600 binary alloy equilibrium diagrams with reference to the publishers and authors concerned. Unfortunately ternary and quaternary alloy diagrams have been omitted from this edition. A number of references to ternary, quaternary and quinary systems have been included. The section on gas-metal systems gives data on the solubility of hydrogen, nitrogen, oxygen and inert gases in metals. The section on diffusion of metals outlines a number of methods for measuring D and provides tabulated data for tracer impurity diffusion

coefficients, diffusion in homogeneous alloys, chemical diffusion coefficients and chemical diffusion in ternary alloys.

Volume III contains over 300 pages of data on the physical and mechanical properties of metals and alloys at subnormal, normal and elevated temperatures. In the tables of tensile properties at normal temperatures the nominal composition of the alloys is given, followed by the appropriate British and American specification numbers. The data in the tables referring to the properties at elevated and at sub-normal temperatures and for creep, fatigue and impact strength were obtained from a more limited number of tests. In these cases the data refer to particular specimens tested and cannot be relied upon as so generally applicable to other samples of material of the same nominal composition.

The section on electroplating and metal finishing outlines a number of processes for cleaning, anodizing and plating metals. However the data on anodizing processes for aluminium does not refer to hard anodizing or to the importance of sealing the oxide coatings to give optimum corrosion resistant properties. Plating processes are outlined but without reference to specification numbers.

The three volumes of some 1,147 pages with contributions from 51 distinguished scientists undoubtedly represents a valued work of reference to the field of metallurgy and metal physics and can be thoroughly recommended.

H. Goldie

**Teach Yourself Acoustics.** By G. R. Jones, et al. Pp. 175. London; English Universities Press Ltd., 1967. Price 10s. 6d.

This is an addition to the popular series of "Teach Yourself" books. Its stated aim is to give a basic understanding of the principal aspects of acoustics so that matters acoustical can be appreciated; this, it competently achieves.

A very wide field is covered, from fundamental concepts and wave propagation theory, through hearing, Hi-Fi, environment, reproduction, noise and the law, to the latest medical and industrial applications.

Generally, little progress can be made in acoustics without resort to mathematical treatment. The mathematics in this book are kept to the barest minimum, but, because the descriptions are clearly and concisely written, the reader will finish with an extensive store of accurate and interesting data.

The book can certainly be recommended to new entrants to the somewhat obscure field of acoustics.

C. Harrington

**Microbiological Methods.** 2nd Edition. By C. H. Collins. Pp. xii-404. London; Butterworth & Co. (Publishers) Ltd., 1967. Price 62s.

The dramatic success that attended the introduction of penicillin in World War II was followed by an intensive search by the biologists of many countries for new and more effective antibiotics, and marked the beginning of a period of intense activity and progress in microbiology.

Yet despite the rapid advances made in the post-war years and the increasing importance of this science to industry, there is clearly a shortage of reliable textbooks on the subject.

It is pleasing therefore to note the success of Mr. Collins's work, which, first published in 1964 and reprinted last year, has now appeared in a second and enlarged edition.

The book is conveniently arranged in four parts, and in Part I the reader is introduced to the fundamentals of microbiology, and given a clear and concise account of the general characteristics of bacteria, yeasts and moulds, their classification and cultivation, together with some guidance on antibody-antigen reactions and serology.

Part II describes in detail the apparatus and equipment of the microbiological laboratory, and includes chapters on sterilization, the use and care of the microscope, preparation of culture media, methods of growing micro-organisms and estimating their numbers, and has a valuable list of biochemical and other tests. A chapter on Complement Fixation has been contributed by the Director of the Public Health Laboratory, Colindale.

Under the title "The Main Groups of Micro-organisms", Part III surveys many important genera and species of bacteria, and provides numerous methods for their identification, but only one small chapter each is devoted to the yeasts and moulds, while viruses and protozoa are excluded entirely.

The final section of the book, entitled "Applied Microbiology" is in effect, a detailed account of the various methods and techniques employed in Public Health laboratories for the examination of water and food supplies, the testing of disinfectants and antibiotics, and the investigation of such matters as food poisoning and dishwashing and kitchen sanitation.

The book concludes with a short selected bibliography for further reference and a useful list of suppliers of laboratory apparatus and equipment.

It is evident that a great deal of the author's personal experience and much patient research have gone into the preparation of this book, and it is perhaps inevitable that his preoccupation with the medical aspects of the subject should be reflected in its pages, and that undue prominence is given to the pathogens.

The book is intended for students preparing for the examinations of the Institutes of Medical Laboratory Technology and Science Technology and for those seeking Higher National Certificates, Diplomas and similar qualifications in Biology. It contains a wealth of up-to-date practical information, and as a textbook and a work of reference it will be warmly welcomed by all students of microbiology.

K. Hunter

**The Design Method.** Edited by S. A. Gregory. Pp. xiii + 354. London; Butterworth & Co. (Publishers) Ltd. 1966. Price 95s.

This well produced and printed volume records the Proceedings of a Symposium held in September 1965 at the Birmingham College of Advanced Technology. The volume has been edited by S. A. Gregory on behalf of the Design and Innovation Group, University of Aston in Birmingham.

A total of thirty-five papers are reprinted divided under six sections:— The Design Method; The Human Perspective; The Elements of Design; Design Techniques; Management and Design; and Design Research. The book is very efficiently indexed and a reasonably detailed Glossary and Bibliography are appended. Unfortunately however the bibliography does not cover all the references in the papers, and this will tend to spoil one of the aims of the editor which is "the use of the book for studies in the philosophy of engineering to suit requirements of the Council of Engineering Institutions."

The subject covered by this Symposium is one which causes animated discussion, argument and disagreement between practising design engineers. It sets out proposals

for differing design disciplines so that the design process is rationalised and may eventually become a mechanical procedure. This is completely opposed to the "engineering genius" of an individual where the design ability is more allied to a pure art form, the outstanding example being, of course, Leonardo da Vinci.

The book does not concern itself with the arguments for and against a formalised design method. I think this is a pity as it would have enhanced the appeal and readability of the work. It may be that such arguments formed part of the discussion on the papers at the Symposium, but these proceedings fail the reader on this subject. This is my greatest criticism of the volume; the editor states that "the discussion was fully recorded on tape but was subject to a marked amount of editorial work in order to provide readability and appear as editorial comment." This editorial action has for me deprived the book of that spark of controversy which is so welcome in the proceedings of Engineering Institutions. The editing has been done so well that it is impossible to distinguish between the paper and discussion.

I have observed the design method being put into action at a large Midlands engineering group and I have been impressed by the results. If this book does nothing else but stimulate discussion, and encourage engineers and designers to a more logical, procedural and critical evaluation in the design stage, it will have proved its value. Paper, after all, is the cheapest commodity available to a designer, and it is cheaper and more efficient to use a logical design method to produce a sound design on paper than to present inspired "back of an envelope" sketches to a workshop for a model which will be the subject of further "inspired" modifications.

I commend this volume to designers of all disciplines, they should all be able to gain some assistance from a selection of the papers printed in it. This also applies to drawing office staffs and it may encourage them to realise that the attitude which is often taken that "the first design is the best design" is rarely correct.

A. W. Nancarrow

**Statistical Methods and Formulae.** By C. G. Lambe. Pp. x + 160 + 20 tables. London; English Universities Press Ltd. 1967. Price 27s. 6d.

Many non-specialist users of statistical techniques, after an interminable search for a half-remembered formula, must have wished for a convenient summary reference book. Dr. Lambe, who is Associate Professor of Mathematics at the Royal Military College of Science, Shrivenham, has produced such an *aide-memoire*, and has made it self-contained by adding a selection of tables, most of them extracted from a new set computed by the Lanchester College of Technology.

The layout of the book is excellent. Formulae are listed on the right-hand page; explanations—mainly, and laudably, as worked examples—are on the facing left-hand page. Topics include basic probability theory, standard distributions, significance tests, regression and curve-fitting, correlation, sampling and quality control, and oddments such as probit analysis, index numbers and time series. For each topic a bibliography is given; this is short and exclusively British, but is nevertheless adequate and caters for all levels of understanding. The

tables, generally of 4-figure accuracy, are sufficient for most purposes, and include useful rarities such as log factorials and random normal deviates. A helpful feature in each cumulative table is a small diagram showing the range of integration. Although some of the tables are somewhat cramped in size, and all are printed in the equal-height type condemned by Comrie, they are reasonably convenient in use.

Unfortunately, the book is deficient in the most important feature of such a tabulation, viz. accuracy. It is not argued by the reviewer that minor errors (such as 50·25 for 50·5 in example 2 on page 10; or reference to equation (8·12) when (8·14) is meant) are in themselves damning; they do, however, tend to destroy the user's confidence, and leave him feeling that he ought to check the accuracy of any formulae he uses—thereby vitiating the prime purpose of the book. Similarly, to find that in formula (3·13) the letter 'r' is used to denote both the r'th percentile and the r'th grouping interval suggests a disturbing lack of care in preparation. Confidence is finally shattered with the discovery of a seriously misleading error in the variance ratio test (which is involved frequently). The listed formulae all discuss significance at the 5% and 1% levels, and consistently refer to the use of Table 7. This table indeed is headed "Percentage Points of the F-Distribution, Two Tails", and is tabulated at the 5% and 1% points. On examination, however, it appears that the mysterious description "Two Tails" means simply that this is the standard F-distribution at the 2½% and ½% points. The correct table to use (and this is confirmed in one of the examples) is Table 6 (which is headed "..., One Tail"). This error, it is clear, could be a trap for the unwary. To add to the confusion, Chapter 21 refers to the use of two stars for significance at the 2% level (for which no table is given!).

Another test of a summary of this kind is its completeness. This is more difficult to define; the interests of the author must colour his selection of topics. (For example, the reviewer would have preferred to see queuing theory included in preference to the controversial index numbers). It is, however, a legitimate criticism that although "probability" is defined (in a remarkably contradictory manner!) and rules for compounding independent probabilities are given at some length, the important concepts of conditional probability, Bayes Theorem (and inverse probability), and likelihood, do not appear at all in the formal text. Instead these terms appear, undefined, as bracketed comments on Example 14 on page 24. Again, in the Chi-squared test, no mention is made of, nor are tables given for, rejection at the 90%, 95% and 99% levels ("too good" a fit). Perhaps the moral standard at Shrivenham is so high that "cooked" data are inconceivable! Against these omissions, nevertheless, it must be said that many useful rarities are included (e.g. Sturges's Rule for optimum grouping—which was new to the reviewer—and tests for randomness of series).

In summary, this is an excellent idea, marred by less-than-perfect execution. Even so, for anyone who is prepared to do a once-for-all verification of doubtful points, it is good value at 27s. 6d.

One plea to the publishers may be added. Inevitably, in a book of this kind, the owner will want to add his own notes of formulae and techniques. A few more blank pages on which to write would be a real boon.

M. J. Daintith



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